

CA2ONEV 5881A36

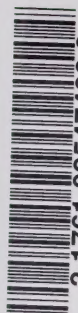
Ontario. MOE.

ARB-36-81-SES

SUDBURY ENVIRONMENTAL STUDY. A STATISTICAL MODEL TO
ESTIMATE LONG-TERM CONCENTRATIONS OF POLLUTANTS
ASSOCIATED WITH LONG-RANGE TRANSPORT AND ITS APPLICATION
TO EMISSIONS FROM THE SUDBURY REGION. / Venkatram, A.

ISBN 0-7743-6962-0

CA2ONEV 5881A36



3 1761 09547438 3

SUDBURY ENVIRONMENTAL STUDY

A Statistical Model to Estimate Long-Term Concentrations of Pollutants Associated with Long-Range Transport and its Application to Emissions from the Sudbury Region

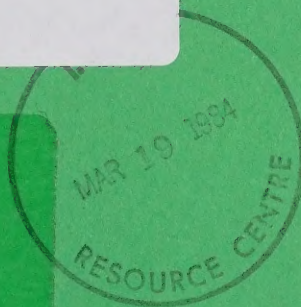
Report No. ARB-36-81-SES

Earth Sciences Library

INST. FOR ENVIRONMENTAL STUDIES
UNIVERSITY OF TORONTO



3 1761 03882605 3



Ontario

Ministry
of the
Environment

The Honourable
Keith C. Norton, Q.C.,
Minister

Gérard J. M. Raymond
Deputy Minister

Sudbury Environmental Study
Co-ordinator: E.W. Piche
Ontario Ministry of the Environment
6th Floor, 40 St. Clair W.
Toronto, Ontario
Canada M4V 1P5

A Statistical Model to Estimate
Long-Term Concentrations of Pollutants
Associated with Long-Range
Transport
and its Application to Emissions
For the Sudbury Region

by

A Venkatram, B.E. Ley and S.Y. Wong

Air Resources Branch
Ontario Ministry of the Environment
880 Bay Street, 4th Floor
Toronto, Ontario M5S 1Z8

Report Number ARB-36-81-SES

September 1981

- 1981 Her Majesty the Queen in Right of Ontario



Digitized by the Internet Archive
in 2025 with funding from
University of Toronto

<https://archive.org/details/31761095474383>

SUMMARY

A simple statistical model is presented for estimating long-term concentrations of pollutants associated with long-range transport. Dispersion and removal of pollutants are described in terms of statistics of these physical processes. The model has been used to estimate wet deposition of sulfur over a grid covering Northeastern United States and Canada and model estimates compare well to corresponding measurements of annual deposition. The model was then applied to estimate the relative contribution of major Sudbury region sulfur dioxide emitters, INCO and Falconbridge.

Four emissions scenarios were considered. First was the 'base case' emission inventory where INCO and Falconbridge's emissions were represented by 1977 amounts. Second was the strike/shut-down emission scenario and third was an SO₂ emission inventory based on the December, 1980 emission limits. The fourth inventory was calculated from Falconbridge's December 1980 emission limit and the August 28th, 1980 Control Order limit for INCO effective January 1, 1983.

The model estimate for the 'base case' emissions showed that the Sudbury region contributed 5 - 30% of the total sulfur deposited during precipitation in most of north-central Ontario and western Quebec. Falconbridge contributed 1 - 5% while the remaining portion was due to INCO's emission except for a small area and small-point source contribution which did not exceed ½%.

The second emission scenario was chosen to show the change in the long-term deposition of sulfur in rain that a reduction in emissions equivalent to the strike/shut-down emissions would cause. For this scenario total 1978 and 1979 emissions for INCO and Falconbridge were averaged to estimate an emission representative of this period. The model result for this scenario showed that the Sudbury region contributed 2 - 20% of the total sulfur deposited in rain in north-central Ontario and western Quebec. Similar reductions from the 'base case' are seen for the individual large emitters.

The emission inventory for the third case represented INCO and Falconbridge emissions by the December, 1980 maximum limits defined by their Control Orders. For this scenario Sudbury's contribution to deposition in north-central Ontario and western Quebec was estimated to be approximately 3 - 25%.

The fourth scenario modeled the long-term contribution of major Sudbury emitters assuming INCO's emissions are the maximum allowable as of January 1, 1983. The results of this simulation showed in north-central Ontario and western Quebec emission from the Sudbury region would have contributed 2 - 23% of the total sulphur deposited during precipitation. Reducing the model emissions for the Sudbury region from 1977 to projected 1983 levels decreased this area's contribution to wet deposition in Muskoka-Haliburton over a long time period by as much as 7% of the total 1977 wet deposition.

Care must be taken in the interpretation of these results. We emphasize that the model results are estimates of long-term long-range wet deposition rates expressed in annual amounts and should not be expected to compare well with measurements taken either near the emission sources or over short periods of time.

TABLE OF CONTENTS

Summary	i
Table of Contents	iii
List of Tables	iv
List of Figures	v
Introduction	1
Scavenging Model	2
Dispersion Model	5
Emission Inventory	7
Specification of Dispersion Parameters	8
Scavenging Parameters	10
Model Testing	13
Examples of Model Applications	15
Estimated Annual Wet Sulfur Despositon Due to Emissions from the Sudbury Region	16
Conclusions	19
List of References	20
Tables	
Figures	27
Appendix A	A1

LIST OF TABLES

- Table 1. Model parameters used in simulations.
- Table 2. Comparison of model predictions with observations of wet deposition of sulfur for 1977 (Galloway and Whelpdale, 1980).
- Table 3. Model emission inventory for the Sudbury Region.

LIST OF FIGURES

- Figure 1. Schematic diagram of the scavenging model.
- Figure 2. Distribution and relative magnitude of model SO₂ emission inventory.
- Figure 3. Model predictions of annual wet deposition of sulfur in gm/m²/year. Stars in figure correspond to monitors in the CANSAP and U.S. networks. Numbers next to stars are station codes referred to in Table 2.
- Figure 4. Relative contribution of SO₂ to the total wet deposition of sulfur.
- Figure 5. Percentage contribution of Canadian SO_x sources to the wet depositon of sulfur.
- Figure 6. Percentage contribution of U.S. SO_x sources to the wet deposition of sulfur.
- Figure 7. Sulfur dioxide emission records and current maximum emission limits for the major emitters in the Sudubry area.
- Figure 8. Percentage contribution of SO_x sources in the Sudbury region to the total wet deposition of sulfur.
- Figure 9a. Percentage contribution of SO_x emissions from INCO to the total wet deposition of sulfur.
- Figure 9b. Percentage contribution of SO_x emissions of SO_x emissions from Falconbridge to the total wet deposition of sulfur.
- Figure 10. Percentage contribution of SO_x sources in the Sudbury region to the total wet deposition of sulfur during the strike/shut-down years 1978-79.

- Figure 11a. Percentage contribution of SO_x emissions from INCO to the total wet deposition of sulfur during 1978-79.
- Figure 11b. Percentage contribution of SO_x emissions from Falconbridge to the total wet deposition of sulfur during 1978-79.
- Figure 12. Estimated percentage contribution of SO_x sources in the Sudbury region to the wet deposition of sulfur assuming INCO's emissions are the maximum currently (Dec. 1980) allowable under the August 28, 1980 Control Order and Falconbridge's emissions are the maximum currently allowable.
- Figure 13a. Estimated percentage contribution of SO_x emissions from INCO to the wet deposition of sulfur assuming INCO's emissions are the maximum currently allowable under the August 28, 1980 Control Order.
- Figure 13b. Estimated percentage contribution of SO_x emissions from Falconbridge to the wet deposition of sulfur assuming Falconbridge's emissions are the maximum allowable under the current limits.
- Figure 14. Estimated percentage contribution of SO_x sources in the Sudbury region to the wet deposition of sulfur assuming Falconbridge's emissions are the maximum currently allowable and INCO's emissions are the maximum allowable after December 31, 1982, under the August 28, 1980 Control Order.
- Figure 15a. Estimated percentage contribution of SO_x emissions from INCO to the wet deposition of sulfur assuming the same emission limits as in Figure 14 for Falconbridge and INCO.
- Figure 15b. Estimated percentage contribution of SO_x emissions from Falconbridge to the wet deposition of sulfur assuming the same emission limits as in Figure 14 for Falconbridge and INCO.

INTRODUCTION

Several studies have shown that relatively simple models can provide acceptable estimates of long-term SO_2 and SO_4 concentrations associated with long-range transport. Using a numerically efficient statistical model Fisher (1978) has been able to compute sulfur deposition rates which are comparable to those obtained from models such as that developed by Eliassen (1978; see also Johnson et al., 1978) which require considerable more data input as well as computational effort. In a recent paper, Fay and Rosenzweig (1980) have shown that a simple analytical model based on the two-dimensional diffusion equation is capable of yielding SO_2 and SO_4 concentration estimates which compare rather well with measurements made over the United States. Thus, there is empirical evidence that simple models "work". The long range transport model presented in this paper is based on this idea. We will show that it incorporates useful features which represent improvements over earlier work.

Our model is statistical in the sense that the physics of transport is parameterized in terms of statistical parameters. The basic premise of this class of models is that long-term concentrations are insensitive to short-term fluctuations in meteorology. It is assumed that concentrations averaged over periods of the order of a year reflect "mean" patterns of the large scale meteorology. This allows us to take a simple approach to the modeling of long-range transport.

The model described in this paper consists of two components, namely the scavenging and the dispersion submodels, each of which will be described separately. Then we will demonstrate the use of the model by comparing wet sulfur deposition estimates with measurements presented by Galloway and Whelpdale (1980) and, finally, we will apply it to the estimation of the annual wet deposition of sulfur from emissions in the Sudbury region.

SCAVENGING MODEL

The treatment of the removal of sulfur is similar to that proposed by Rodhe and Grandell (1972) and used by Bolin and Persson (1975) and more recently by Fisher (1978). However, this submodel is more "physically" based and it will be seen that it is capable of handling more general physical situations than those by the model of Rodhe and Grandell (1972).

The model is based on the idea of classifying pollutant particles and "wet" and "dry". Wet particles exist during precipitation and dry particles during dry periods. On a long term, every travel time from a source is associated with a certain amount of dry particles and a certain amount of wet particles. Using this concept we can formulate differential equations for the evolution of these particles as a function of travel time from the source. Before doing so we will clarify a few concepts. Wet particles, released during precipitation, retain their identity until they encounter a dry period. Following Rodhe and Grandell (1972) we will assume that the average rate of "conversion" from wet to dry particles is inversely proportional to the average length of wet periods in a Lagrangian sense. A similar assumption can be made regarding "conversion" of dry particles to wet particles. Further, we will assume that the scavenging coefficients do not vary with travel time. However, they are different for wet and dry periods. If we denote SO_2 by G and SO_4 by S , their evolution can be conveniently shown in Fig. 1. In the figure, λ refers to the SO_2 scavenging coefficient, k is the SO_2 to SO_4 conversion rate, λ is the SO_4 scavenging coefficient, τ is the average length of wet or dry periods, and subscripts 'd' and 'w' refer to dry and wet particles. We see that the 'species' G_d (dry SO_2) is depleted through dry deposition (λ_d), conversion to sulfate (k_d) and conversion to wet SO_2 ($1/\tau_d$). We also note that wet SO_2 is converted to dry SO_2 at a rate given by ($1/\tau_w$). The evolution of sulfate as a function of travel time is modeled in a similar manner. It is important to note that the particular form of the conversion from dry to wet particles or vice versa is based on the assumption that the cumulative frequency distribution of wet or dry periods is exponential (Rodhe and Grandell, 1982). From the diagram we can immediately write down the equations for G and S .

$$\frac{dG_d}{dt} = -\lambda_d G_d - k_d G_d - \frac{1}{\tau_d} G_d + \frac{1}{\tau_w} G_w \quad (1a)$$

$$\frac{dG_w}{dt} = -\lambda_w G_w - k_w G_w - \frac{1}{\tau_w} G_w + \frac{1}{\tau_d} G_d \quad (1b)$$

$$\frac{dS_d}{dt} = -\bar{\lambda}_d S_d + \bar{k}_d G_d - \frac{1}{\tau_d} S_d + \frac{1}{\tau_w} S_w \quad (2a)$$

$$\frac{dS_w}{dt} = -\bar{\lambda}_w S_w + \bar{k}_w G_w - \frac{1}{\tau_w} S_w + \frac{1}{\tau_d} S_d \quad (2b)$$

If Q_{SO_2} and Q_{SO_4} denote the amount of SO_2 and SO_4 released at the source we can write

$$G_d(0) = f_d Q_{SO_2}; \quad G_w(0) = f_w Q_{SO_2} \quad (3a)$$

$$S_d(0) = f_d Q_{SO_4}; \quad S_w(0) = f_w Q_{SO_4} \quad (3b)$$

In (3), f_d and f_w are the fractional dry and wet periods at the release point. With (3) the solutions of (1) and (2) readily follow

$$G_d = \sum_{i=1}^2 A_{di} e^{\alpha_i t}; \quad G_w = \sum_{i=1}^2 A_{wi} e^{\alpha_i t} \quad (4a)$$

$$S_d = \sum_{i=1}^2 B_{di} e^{-\gamma_i t} + \sum_{i=1}^2 \beta_{di} e^{\alpha_i t}; \quad (4b)$$

$$S_w = \sum_{i=1}^2 B_{wi} e^{-\gamma_i t} + \sum_{i=1}^2 \beta_{wi} e^{\alpha_i t}$$

Details of the solution are given in the appendix.

After writing this paper we learnt that F.B. Smith (1980) has developed a scavenging model based on equations almost identical to ours. In his paper he provides considerable physical insight into the meaning of wet and dry periods which determine the particle "type" as used in our model. He also considers the effect of the variation of rainfall rates on the evolution of G and S . The

significant conclusion of his study is that it is necessary to differentiate between mobile wet and dry synoptic regions in order to make realistic estimates of sulfur deposition.

It is seen from the formulation of the model that we can specify different removal rates for dry and wet periods. This can be useful in sensitivity studies. For example, it is easy to test the recent hypothesis (McNaughton and Scott, 1980) that the SO_2 to SO_4 conversion rate is higher during rain than during dry periods.

DISPERSION MODEL

The long-term concentration $\bar{C}(\underline{r}, t)$ at point $\underline{r}$ at time t can be written as (Lamb, 1980)

$$\bar{C}(\underline{r}, t) = Q \int_{-\infty}^t p(\underline{r}, t | \underline{r}_s, t') dt' \quad (5)$$

where Q is the emission rate of the source located at $\underline{r}_s$ and $p(\underline{r}, t | \underline{r}_s, t')$ is the probability density that a particle released at $\underline{r}_s$ at time t' will be found at $\underline{r}$ at time t . If we assume that p can be expressed as

$$p(\underline{r}, t | \underline{r}_s, t') = p(\underline{r} | \underline{r}_s; t - t') \quad (6)$$

Equation (5) becomes

$$\bar{C}(\underline{r}) = Q \int_0^{\infty} P(\underline{r} | \underline{r}_s; \tau) d\tau \quad (7)$$

Note that τ is the time of travel between $\underline{r}$ and $\underline{r}_s$. To proceed further we will assume that scavenging and dispersion are independent. Fisher (1978) and Bolin and Persson (1975) have used this assumption in their models. This then allows us to express p as

$$P(\underline{r} | \underline{r}_s; \tau) = M(\tau) D(\underline{r} | \underline{r}_s; \tau) \quad (8)$$

where $M(\tau)$ depends only on removal mechanisms and $D(\underline{r} | \underline{r}_s; \tau)$ is a function of large scale dispersion. It is easy to see that $M(\tau)$ corresponds to the functions G_d , G_w , S_d and S_w (See Eq. 4) for unit release and is essentially the probability that a particle will survive after a travel time τ .

The dispersion function $D(\underline{r}|\underline{r}_s; \tau)$ will depend on large scale wind patterns. Bolin and Persson (1975) and Shieh (1977) have shown that the Gaussian puff equation is appropriate here

$$D(\underline{r}|\underline{r}_s; \tau) = f(z, \tau) \frac{1}{2\pi \sigma_x \sigma_y} \exp \left[-\frac{(x-\bar{x})^2}{2\sigma_x^2} - \frac{(y-\bar{y})^2}{2\sigma_y^2} \right] \quad (9)$$

where $f(z, \tau)$ describes the vertical dispersion. The parameters of the distribution $\bar{x}(\tau)$, $\bar{y}(\tau)$ are the co-ordinates of the mean particle position after travel time τ from the release point. The dispersion parameters $\sigma_x(\tau)$ and $\sigma_y(\tau)$ correspond to standard deviations of particles about $(\bar{x}, \bar{y})$ after travel time τ from the source. These parameters can be determined from trajectory statistics as suggested by Bolin and Persson (1975).

EMISSION INVENTORY

Figure 2 depicts the distribution and relative magnitude of the points which comprise the sulfur oxides in this study. The emission data for the model were collected from several sources. In the northeastern sector of the US it was compiled from the EPA point source inventories (Benkowitz; 1979) and the GCA (consulting company contracted by EPRI) major point and area source records. The Canadian emission points except in Ontario were taken from the AES preliminary point and area source inventory (Voldner et al., 1980). The Ontario points were extracted from the Ontario Ministry of the Environment sulfur emissions inventory.

Since we wished to limit the required computational resources, when feasible, we lumped sources together. All large (> 100 kTonnes $\text{SO}_2/\text{yr.}$) point sources listed in the above mentioned emissions data and 95% of the major (> 10 kTonnes $\text{SO}_2/\text{yr.}$) point sources were incorporated into the model's inventory (usually grouped) to form effective point sources located at the emissions-weighted geometric means of the co-ordinates of the contributing points. Care was taken to amalgamate only sources situated in similar geographic settings and, in general, less than 50 km apart. Approximately 60% of all area emissions and 72% of all minor point emissions were incorporated into the inventory shown in Figure 2 by adding minor point sources and area sources located near (≈ 50 km) major points to that point or combining small sources concentrated in large urban centers to form effective point sources. Area emissions represent approximately 10% of the total emissions while small point sources account for about 17% of all SO_2 emissions.

SPECIFICATION OF DISPERSION PARAMETERS

The wet and dry deposition of sulfur depends on the vertical distribution of the pollutant as well as the turbulence in the diurnally varying planetary boundary layer. These factors have to be accounted for in modeling deposition and concentration fields averaged over time scales of the order of a day. However, Maul (1980) shows that estimates of annual averages of these variables are relatively insensitive to the details of the vertical concentration distribution. Furthermore, Eliassen and Saltbones (1975) and Johnson et al. (1978) have successfully predicted long-term averages, assuming that sulfur is well-mixed through a boundary layer which is invariant in space and time. On the basis of these studies we took the distribution of SO_2 and SO_4 to be uniform in the vertical through the depth of a constant mixed layer. We should point out that this limits the resolution of the model to distances of the order of 100 km from major sources. Closer to the sources the assumptions of this model may not be appropriate for estimating the local contribution of the emitter.

The large scale horizontal distribution of pollutants is determined by the parameters $\bar{x}$, $\bar{y}$, σ_x and σ_y . For the co-ordinates of the mean motion of large scale eddies we assume that

$$\begin{aligned}\bar{x} &= u \tau \\ \bar{y} &= 0\end{aligned}\tag{10}$$

where u is the mean velocity of synoptic eddies and τ is the travel time from the source. Equation (10) expresses the fact that at mid-latitudes weather systems move from the west to the east. Fay and Rosenzweig (1980) have used this assumption in their modeling exercise.

The analysis of trajectories by Slinn et al. (1979) and Bolin and Persson (1979) suggests that σ_x and σ_y can be expressed as

$$\sigma_x = \sigma_u \tau\tag{11}$$

$$\sigma_y = \sigma_v \tau$$

On the basis of statistical dispersion theory it is reasonable to assume that σ_u and σ_v are the standard deviations of the horizontal velocity fluctuations of synoptic

turbulence. These statistics could be derived by sampling 850 mb winds over periods of the order of years. Tennekes (1977) suggests the following values for the large-scale velocities

$$u = 10 \text{ ms}^{-1}, \sigma_u = 10 \text{ ms}^{-1}, \sigma_v = 6 \text{ ms}^{-1}$$

We should point out that our choice of the horizontal dispersion parameters is tentative. They will be modified when we have completed a statistical analysis of trajectories.

SCAVENGING PARAMETERS

The stochastic scavenging model allows us to distinguish between wet and dry periods. This, as we shall see later, is a useful feature of our long-range transport model.

The transformation of SO_2 to SO_4 is a complex process which depends on a number of physical variables such as solar intensity and ambient ozone concentration, (see Wilson and Gillani, 1979). For long-term modeling we assume that the conversion rate is 1%/hr, a value which is an "average" of field measurements made during dry periods (Wilson and Gillani, 1979).

Our knowledge of the conversion of SO_2 to SO_4 during rain is almost non-existent. There is some indirect evidence (McNaughton and Scott, 1980; MacCracken, 1978) to indicate that incloud conversion of SO_2 to SO_4 can be greater than 10%/hr. Scott (1980) suggests that more than 60% of the sulfur in rain falling in summer is associated with SO_2 . The it is reasonable to assume that the rate at which SO_2 appears as sulfur in rain is limited by the rate at which SO_2 is incorporated into precipitating clouds. The rate at which clouds take up the SO_2 is approximately given by w/z_i where w is the mean updraft velocity at cloud base and z_i is the mixed layer height. w is given by (Smith and Hunt, 1979)

$$w = \rho_w R / M \quad (12)$$

In (12), ρ_w is the density of water, R is the precipitation rate and M is the water content of the air entrained into clouds. Typical values for these variables are $M = 5 - 10 \text{ gm}^{-3}$, $R = 1 \text{ mm/hr}$ and $z_i = 1000 \text{ m}$. We then find that the "effective" washout rate w/z_i for SO_2 is $\approx 3-6 \times 10^{-5} \text{ s}^{-1}$. This suggests that one way of accounting for incloud oxidation of SO_2 to SO_4 is to add an effective washout rate to the actual wet removal rate of SO_2 . An alternative is to increase the oxidation rate during precipitation. McNaughton and Scott (1980) found that a 10%/hr rate was necessary to explain measurements of sulfur in rain.

Washout of SO_2 is a reversible process which is a function of pH of rain. The washout rate decreases with pH. For the range of pH (4 - 5) usually encountered the scavenging rate denoted by j is of the order of 10^{-5} s^{-1} (Garland, 1978). Johnson et al. (1978) use a value of $6 \times 10^{-5} \text{ s}^{-1}$ ($R = 1 \text{ mm/hr}$) in their modeling study while Fisher (1978) is forced to use 10^{-4} s^{-1} to explain the measured values of wet deposition. These relatively high values for j are a consequence of additional

"washout" associated with incloud conversion of SO_2 to SO_4 . We feel that using an increased washout for SO_2 is the most convenient way to account for incloud oxidation. Increasing the conversion rate during precipitation (McNaughton and Scott, 1980) has the unrealistic feature of enhancing the sulfate concentration in the boundary layer.

Maul (1978) has inferred the value of the SO_2 washout coefficient from a time series of ambient SO_2 concentrations. He found that j could be described by the equation

$$j = \alpha R \quad (13)$$

where $\alpha \approx 3 \times 10^{-5}$. The linear dependence of j on R as well as the magnitude of α suggests that the "apparent" SO_2 washout could be dominated by incloud oxidation of SO_2 . This idea appears to be supported by the work of Eliassen and Saltbones (1975) in which sulfur concentration in rain is related to SO_2 rather than SO_4 concentration. The effective j used in their study is $\approx 4.0 \times 10^{-5}$. On the basis of these cited values for j we used $3 \times 10^{-5} \text{s}^{-1}$ in our work.

The precipitation scavenging of sulfate is represented by a linear removal rate $\bar{j}$. This assumption used by several authors (Fisher, 1978; Johnson et al., 1978) is clearly unrealistic for modeling precipitation events. However, it is probably less critical for long-term estimates of wet deposition. In our study we used 10^{-4}s^{-1} on the basis of Garland's review paper (1978).

Measurements indicate that the dry deposition velocity v_d of SO_2 is of the order of 1 cm s^{-1} during daytime. As suggested by Fisher (1978) we used $v_d = 0.5 \text{ cm s}^{-1}$ to compensate for reduced deposition during stable nocturnal conditions.

Sulfate is primarily in the form of aerosol whose median diameter is below $1 \mu\text{m}$ (Garland, 1978). For this particle size range the deposition velocity is around 0.1 cm s^{-1} . We used $\bar{v}_d = 0.05 \text{ cm s}^{-1}$ for the reason given in the preceding paragraph.

We have little guidance on the magnitude of the parameters τ_d and τ_w . As they are Lagrangian variables defined with respect to trajectories of air parcels they cannot be derived from routinely available Eulerian (fixed point) meteorological observations. Rodhe and Grandell (1972) have estimated these parameters assuming a ratio between fixed point and Lagrangian measurements.

Slinn et al. (1979) have made more reliable estimates based on actual trajectories originating from Kansas city. The averages of the January and July 1975 values are $\tau_D=46$ hours and $\tau_W=7$ hours which are comparable to those suggested by Rodhe and Grandell (1972). Our studies showed that model results are relatively insensitive to τ_D and τ_W , a conclusion which is in agreement with that found by Smith (1980).

Table 1 presents the model parameters used in our simulations. The values of f_D and f_W are similar to those used by Fisher (1978).

MODEL TESTING

The model described in the previous sections has been used to compute sulfur in rain falling over the grid system shown in Fig. 2. The long-term sulfur deposition has been computed from

$$D_w = \left[\frac{1}{2} \bar{C}_{SO_2} j + \frac{1}{3} \bar{C}_{SO_4} j \right] z_i \quad (14)$$

Figure 3 shows contours of D_w obtained from the model. The emission inventory used corresponds to the year 1977. The figure also shows the locations of monitors set up by Canada and the United States to sample precipitation chemistry. The description of the network and the corresponding annual deposition values are given in the paper by Galloway and Whelpdale (1980).

Table 2 presents the comparison between the model predictions of sulfur wet deposition and the observations. Based on values suggested by Fisher (1978) we used a background deposition of $0.2 \text{ gm}^{-2}\text{s}^{-1}$. It is seen from the table that model predictions of wet deposition in the CANSAP (Whelpdale and Berry, 1978) network are generally lower than the observed values. However, the model explains 76% of the measured variance in the deposition. Rejecting the value at receptor 11 as an outlier increases the r^2 to 0.84. According to Whelpdale (personal communication) the measurement technique used in the CANSAP network might have led to an overestimation of the observations by about 30%. This should explain the predictions being lower than the measured values. It is interesting to find that regressing predictions against observations reduced by 30% results in $a = 0.17 \text{ gm}^{-2} \text{ yr}^{-1}$ and $b = 1.04$ (regression coefficients).

The ratio of observations to predictions for the American data is distributed fairly evenly around the ideal value of unity. However, the r^2 is insignificant at 0.09. Removing the outliers at receptors 24, 25, 26 results in a marked increase of the r^2 to 0.47. We believe that the discrepancy between model estimates and measurements is related to the fact that the American data have been drawn from a number of sources which are not likely to be consistent in quality (Galloway and Whelpdale, 1980).

Note that model testing is anything but straightforward. This is because the correspondence between model predictions and observations is very difficult to establish. The model estimate is designed to correspond to the mean of the concentration distribution to which the measured value is assumed to belong. Therefore, we expect model predictions to deviate from observations. At the present time we have little information on this expected deviation and we cannot avoid a certain degree of subjectivity in evaluating model performance. For a discussion of this problem the reader is referred to Venkatram (1979).

The classification of "outliers" in the data is not based on an objective criterion. But then we have rejected only 4 out of 26 points. It is useful to point out that 77% of the observations are within a factor of two of the predictions. Based on "experience" with air pollution modeling we believe these model estimates of wet deposition of sulfur are acceptable.

We should point out that model parameters used in this paper represent "standard" values quoted in literature (See Eliassen, 1980, for a review). We did not drive optimum values by "fitting" observations to model predicted depositions. This we believe lends credibility to the evaluation of the model.

EXAMPLES OF MODEL APPLICATIONS

The model can be used to estimate dry deposition. However, since lack of data would not allow testing of model calculations, we have chosen to show only examples of applications of wet deposition estimates. Before doing so, we should point out an interesting aspect of sulfur deposition. Figure 4 shows the contribution of SO_2 to the total wet deposition of sulfur. It is seen that wet deposition of sulfur is dominated by the apparent washout of SO_2 . This is clearly at variance with measurements (Dana, 1980) which indicate that SO_2 contributes no more than 40% to the sulfur in rain. However, the result tends to support the theory that inclusion of oxidation of SO_2 to SO_4 is very important. As mentioned earlier the simplest method of including this process in a model is to use a high "apparent" SO_2 washout rate. It is interesting to note that other modelers (Fisher, 1978; Johnson et al., 1978) have used SO_2 wet removal rates which are comparable to that used by us.

Figures 5 and 6 show the relative contributions of the U.S. and Canada to the wet deposition of sulfur. This type of information is useful for abatement plans in relation to the acid rain problem. It is seen that south of latitude 45° more than 50% of the sulfur deposited in rain can be attributed to U.S. sources. Canadian sources in Sudbury and Noranda are major contributors primarily in regions in their vicinity. Note that background deposition of $0.2 \text{ gm}^{-2}\text{yr}^{-1}$ is dominant in Northern Canada.

ESTIMATED ANNUAL WET SULFUR DEPOSITION DUE TO EMISSIONS FROM THE SUDBURY REGION

Sulfur dioxide emissions in the Sudbury region are dominated by two major emitters, INCO and Falconbridge. During the mid-1970's these sources combined to emit approximately 1340 thousand, metric tonnes of sulfur dioxide annually. Figure 7 depicts of sulfur dioxide emissions from Falconbridge and INCO during the past ten years. From this data the 1977 emissions were selected as representative of the mid-1970's time period and, therefore, compatible with available emissions data for other sources in northeastern North America. Emission inventories for long-range transport modeling always contain somewhat historical (3 - 6 years) data due to the large volume of data and the many agencies involved in their collection and preparation.

The statistical model described and evaluated earlier in this report will now be used to analyse several emission scenarios. For this study the wet deposition of sulfur from sources in the Sudbury area will be estimated using the model parameters summarized in Table 1. However, before proceeding to describe the model results we will briefly discuss the temporal and spatial scope of the model with reference to the major emitters in the Sudbury region.

The statistical model is based on the assumption that annual average meteorology can be used to describe long-term advection and dispersion of the pollutant. Intuitively this seems correct and the success with which the model estimates compare with the corresponding measurements of annual wet deposition of sulfur (Table 2) gives substance to this theory. However, the process of averaging removes short-term and small scale events and, as a result, the model only provides an estimate of average deposition over periods of the order of a year. Consequently all emission scenarios selected for Sudbury region have been chosen to represent long-term average emissions. For example, the regional emissions for the 1978-1979 strike/shut-down period will be represented by the two-year annual average emission while the actual emissions may have varied from almost no emissions to nearly full production.

The current model parameterization assumes instantaneous vertical homogeneity with all the pollutant emitted into the mixed layer. As a result, all processes or events occurring on the time/space scales less than those required for mixing to vertical homogeneity cannot be resolved by this model. The assumption of instantaneous vertical homogeneity is particularly questionable near the INCO, 381 m chimney which, in 1977, emitted approximately 80% of the Sudbury region's

SO₂ emissions. Frequently plumes released at this height are trapped above the mix layer and may travel large distances before being vertically dispersed.

Four emission scenarios will now be discussed. First will be the 'base case' emission inventory where INCO and Falconbridge's emissions are represented by 1977 amounts. Second will be the strike/shut-down emission scenario and third will be an SO₂ emission inventory based on the December, 1980 emission limits. The fourth inventory will be calculated from the current emission limit for Falconbridge and the August 28th, 1980 Control Order limit for INCO effective January 1, 1983. These emission scenarios are summarized in Table 3.

Figure 8 displays the model estimate of the relative contribution of sources in the Sudbury area to the total wet deposition of sulfur assuming the 'base case' emissions for INCO and Falconbridge. The relative contribution of the Sudbury region is the ratio of the wet deposition of sulfur due to INCO, Falconbridge and other regional sources and the total wet deposition due to all sources in northeastern North America. The model estimate of the total wet deposition of sulfur due to all sources is shown in Figure 3 and is discussed earlier in this report. The relative deposition patterns for INCO and Falconbridge are displayed separately in Figures 9a and 9b respectively.

The model estimate shows sources in the Sudbury region contribute 5 - 30% of the total sulfur deposited during precipitation in most of north-central Ontario and western Quebec. Near Sudbury the model predictions exceed 30%; however, as discussed earlier this close to the source the long-range transport model is no longer applicable. Comparison of Figures 8 and 9a show that during the mid-1970's INCO's emissions dominated the wet deposition due to sulfur emitted from the Sudbury region. However, Falconbridge (Figure 9b) did contribute a significant amount (1 - 5%) of the total sulfur deposited during rain in the central and northern portions of Ontario and in western Quebec.

Sulfur dioxide emissions from the Sudbury area were greatly reduced by shut-downs and strikes during the 1978-1979 period. To provide an estimate of the influence of this reduction on the long term pattern of wet sulfur deposition we calculate next the relative deposition pattern for Sudbury using INCO and Falconbridge two-year average annual emissions for 1978-1979. When calculating the relative deposition amounts the total wet deposition of sulfur from all northeastern North American sources is re-evaluated to reflect the reduced emissions from the Sudbury area but all other emissions are assumed unchanged from their 'base case' values.

The results of this reduced emissions scenarios are shown in Figure 10 and the individual relative contributions of INCO and Falconbridge are depicted in Figures 11a and 11b respectively. The effect of essentially halving the regional SO₂ emissions is obvious from the comparison of Figures 8 and 10. The model estimates show a reduction in wet sulfur deposition from 5 - 30% for the 'base case' to 2 -20% for the reduced emissions scenario over approximately the same region of north-central Ontario and western Quebec. The intent of this scenario is not to model deposition measurements during the strike/shut-down period since reductions in emissions during this time occurred as intervals of limited or no emissions rather than as an average decrease over the entire period. What the simulation does show is the change in the long-term deposition of sulfur in rain that an effective halving of Sudbury SO₂ emissions would cause.

The third Sudbury region emission inventory was determined from the December, 1980 maximum emission limits of both INCO and Falconbridge. Based on these Control Orders the maximum annual emission was calculated assuming the daily maximum was emitted 365 days of the year. For Falconbridge the limit was 465 short tons of SO₂ per day and for INCO (subject to the August 28th, 1980 Control Order) it was 2500 short tons SO₂ per day. Figure 12 depicts the model estimate of the relative deposition pattern for this scenario. As well, for comparison, the relative contributions of INCO and Falconbridge are shown in Figures 13a and 13b respectively. The patterns for this emission inventory represent the maximum contribution of current Sudbury emissions to the long-term average deposition of sulfur at large distances from the emitters. Actual annual emissions are expected to be somewhat less than this limit; hence, Figures 12 and 13 may be considered to present the current upper-bound on the long-term average wet sulfur deposition from Sudbury sources. This upper limit is subject to the assumption that emissions from all other sources have not changed significantly since the mid-1970's.

The final emission scenario considered is based on the maximum allowable SO₂ emission for INCO after January 1, 1983 as defined in the August 28th, 1980 Control Order. For this emission inventory we assume that Falconbridge's emission is the maximum currently allowed while all other sources are assumed unchanged from their mid-1970's annual emission rates. The exception being INCO whose annual emission is assumed to be 1950 short tons of SO₂ per day for 365 days per year. The results of this simulation are shown in Figures 14 and 15. Assuming no change in the magnitude of other sources the pattern in Figure 14 represents an estimate of the maximum contribution of Sudbury region sources to long term average deposition of sulfur during precipitation when INCO is subject to the January 1, 1983 sulfur dioxide emission limit.

CONCLUSIONS

We have shown that a simple statistical model can provide acceptable estimates of sulfur deposition. This supports the conclusions of the studies by Fisher (1978) and Fay and Rosenzweig (1980).

Our study indicates that SO_2 could be a major contributor to the wet deposition of sulfur. This appears to support recent indirect evidence of rapid incloud oxidation of SO_2 and SO . If this is indeed physically correct we can simplify modeling by concentrating on SO_2 .

Wet sulfur deposition in central and northern Ontario and Quebec from Canadian sources is dominated by SO_2 emitted by major smelting plants in Sudbury, Wawa and Noranda (See Figure 5). In the previous section model calculations of the contribution of sources in the Sudbury region are presented for several emission scenarios to estimate the long-term effect of reduced emission amounts. Comparison of these scenarios shows that reducing emissions from Sudbury would significantly reduce this region's contribution to the total deposition of sulfur during rain; however, Sudbury area emissions still would remain a major contributor along with Wawa and Noranda to deposition in the non-industrial area of north-central Ontario and western Quebec.

These modeling results were determined based on the premise that long-term SO_2 and SO_4 concentrations are related to the "average" meteorological conditions (where the averaging time is of the order of years). As a result the model calculations are not comparable to experimental measurements made over relatively short periods of time when the weather conditions may deviate significantly from the "average". For example, the model results are not directly comparable with the results from field experiments for relatively short term events such as the shut down of INCO in Sudbury between September, 1978 and June, 1979.

We realize that some of the assumptions used in the model are questionable. For example, the statistics of dispersion are not based on the analysis of trajectories. This analysis is in progress. Although model parameters are based on values quoted in literature we would like to perform a detailed sensitivity study in the future. Also we plan to incorporate the effect of source height into the model.

LIST OF REFERENCES

- Benkowitz, C., 1979: Compiling a multistate emissions inventory, Brookhaven National Laboratory/MAP3S Report, BNL-26843, Atmospheric Sciences Division, Department of Energy and Environment, Brookhaven National Laboratory, Upton, New York, U.S.A.
- Bolin, B. and Persson, C., 1975: Regional dispersion and deposition of atmospheric pollutants with particular application to sulfur pollution over Western Europe. *Tellus* 27, 281-310.
- Dana, T., 1980: Sulfur wet deposition in the Northeast United States: Winter 1978-1979. Pacific Northwest Laboratory, PNL-3300, UC-11, Annual report for 1979 to the DOE Assistant Secretary for Environment, 42-43..
- Eliassen, A., 1978: The OECD study of long-range transport of air pollutants: Long-range transport modeling. *Atmospheric Environment* 9, 425-429.
- Eliassen, A., 1980: A review of long-range transport modeling. *J. Appl. Meteor.*, 19, 231-240.
- Fay, J.A. and Rosenzweig, J.J., 1980: An analytical diffusion model for long distance transport of air pollutants. *Atmospheric Environment*, 14, 355-365.
- Fisher, B.E.A., 1978: The calculation of long-term sulfur deposition in Europe, *Atmospheric Environment*, 12, 489-501.
- Galloway, J.N. and Whelpdale, D.M., 1980: An atmospheric sulfur budget for Eastern North America. *Atmospheric Environment*, 14, 409-417.

- Garland, J.A., 1978: Dry and wet removal of sulfur from the atmosphere, Atmospheric Environment 12, 349-362.
- Johnson, W.B., Wokf, D.E. and Mancuso, R.L., 1978: Long-term regional patterns and transfrontier exchanges of airborne sulfur pollution in Europe. Atmospheric Environment, 12, 511-527.
- Lamb, R.G., 1980: Mathematical principle sof turbulent diffusion modeling. Article in Atmospheric Planetary Boundary Layer Physics, Elsevier Publishing, Amsterdam, 1980, 429 pp.
- MacCracken, M.C., 1978: Simulation of regional precipitation chemistry. Paper present at EPRI workshop on Acid Precipitation, August 22-25, 1978, Alta, Utah.
- Maul, P.R., 1978: Preliminary estimates of the washout coefficient for sulfur dioxide using data from an East Midlands ground level monitoring network. Atmospheric Environment, 12, 2515-2517.
- McNaughton, D.J. and Scott, B.C., 1980: Modeling evidence of incloud transformation of sulfur dioxide to sulfate. J. Air Pollution Control Association, 30, 272-273.
- Rodhe, H. and Grandell, J., 1972: On the removal time of aerosol particles from the atmosphere by precipitation scavenging. Tellus 24, 442-454.
- Scott, B.C., 1980: Predictions of in-bloud conversion rates of SO₂ to SO₄ based upon a simple chemical and dynamical model. Proceedings of the Second Joint Conference on Applications of Air Pollution Meteorology, March 28, 1980, New Orleans, La., 389-396.

- Shieh, C.M., 1977: Application of statistical trajectory model to the simulation of sulfur pollution over Northeastern United States. *Atmospheric Environment*, 12, 1933-1938.
- Slinn, W.G.N., Katen, P.C. Wolf, M.A., Loveland, W.D., Radke, L.F., Miller, E.L. Ghannam, L.J., Reynolds, B.W., and Vickers, D., 1979: Wet and dry deposition and resuspension of AFCT/TFCT Fuel processing radionuclides. U.S. Department of Energy Final Report SR-0980-10, Air Resources Center, Oregon State University, Corvallis, Oregon, U.S.
- Smith, F.B. and Hunt, R.D., 1979: The dispersion of sulfur pollutants over Western Europe. *Phil. Trans. R. Soc. Long.*, A.290, 523-542.
- Smith, F.B., 1980: The significance of wet and dry synoptic regions on long-range transport of pollution and its deposition. *Atmospheric Environment* (in press).
- Tennekes, H., 1977: The general circulation of two-dimensional turbulent flow on a Beta plane. *J. Atmos. Sci.*, 34, 702-712.
- Venkatram, A, 1979: The expected deviation of observed concentrations from predicted ensemble means. *Atmospheric Environment*, 13, 1547-1549.
- Voldner, E.C., Shah, Y. and Whelpdale, D.M., 1980: A preliminary Canadian emissions inventory for sulfur and nitrogen oxides. *Atmospheric Environment*, 14, 419-428.
- Whelpdale, D.M. and Berry, R.L., 1978: The Canadian precipitation chemistry network. Presented at the 84th Am. Inst. Chem. Engrs. Natn Mtg., Philadelphia, USA.

Wilson, W.E. and Gillani, N.W., 1979: Transformation during transport: a state of the art survey of the conversion of SO₂ to sulfate. WMO Symposium on the Long-range transport of Pollutants and its relation to General Circulation including Stratospheric/Tropospheric Exchange Processes, Sofia, Bulgaria, 1-5 October, 1979, 157-164.

Table 1

Model parameters used in "base" case simulations

1. Scavenging parameters

SO ₂ dry deposition velocity (v_d)	= $0.5 \times 10^{-2} \text{ms}^{-1}$
SO ₄ dry deposition velocity ($\bar{v}_d$)	= $0.05 \times 10^{-2} \text{ms}^{-1}$
Dry period SO ₂ to SO ₄ conversion rate (k_d)	= 1%/hr
Wet period SO ₂ to SO ₄ conversion rate (k_w)	= 1%/hr
SO ₂ wet removal rate (j)	= $3 \times 10^{-5} \text{s}^{-1}$
SO ₄ wet removal rate ($\bar{j}$)	= $1 \times 10^{-4} \text{s}^{-1}$

2. Meteorological parameters

Average mixed layer height (z_i)	= 1000 m
Advecting wind speed (u)	= 10 ms^{-1}
Dispersion velocities (σ_u, σ_v)	= $10 \text{ ms}^{-1}, 6 \text{ ms}^{-1}$
Lagrangian dry period duration (τ_d)	= 46 hr
Lagrangian wet period duration (τ_w)	= 7 hr
Fractional dry period at source (f_d)	= 0.9
Fractional wet period at source (f_w)	= 0.1
Emission ratio at source QSO ₂ /QSO ₄	= 0.98/0.02

Table 2

<u>Station No.</u>	<u>Receptor Name</u>	<u>OBS</u>	<u>PRED</u>	<u>Wet sulfur deposition</u> <u>OBS/PRED</u>
		(gm ⁻² yr ⁻¹)		
1	Kingston, Ont.	1.26	0.93	1.35
2	Moosonee, Ont.	0.58	0.33	1.76
3	Mount Forest, Ont.	2.32	0.96	2.42
4	Peterborough, Ont.	1.81	0.94	1.93
5	Pickel Lake, Ont.	0.39	0.28	1.39
6	Simcoe, Ont.	2.34	1.49	1.57
7	Wawa, Ont.	0.91	0.52	1.75
8	Windsor, Ont.	2.98	2.00	1.49
9	Chibougamau, Que.	1.06	0.42	2.52
10	Maniwaki, Que.	0.71	0.75	0.95
11	Montreal, Que.	2.35	0.88	2.67
12	Merrimach Cnty, N.Y.	0.91	0.93	0.98
13	Albany Cnty, N.Y.	1.20	1.21	0.99
14	Allengany Cnty, N.Y.	2.20	1.58	1.39
15	Dutchess Cnty, N.Y.	1.20	1.48	0.81
16	Essex Cnty, N.Y.	0.84	0.84	1.00
17	Oneida Cnty, N.Y.	1.70	1.08	1.57
18	Onondaga Cnty, N.Y.	0.79	1.19	0.66
19	Ontario Cnty, N.Y.	1.20	1.34	0.90
20	St. Law. Cnty, N.Y.	1.00	0.89	1.12
21	Oak Ridge, Tenn.	1.30	1.04	1.25
22	Charlottesville, Vir.	0.91	1.31	0.69
23	Tucker Cnty, W.V.	2.00	1.94	1.03
24	Washington, D.C.	1.00	1.83	0.55
25	Lewistown, Penn.	0.98	2.21	0.44
26	Paducah, Kentucky	0.57	1.29	0.44

LINEAR ANALYSIS: OBSERVED DEPOSITION = a + b * PREDICTED DESPOSITION

Receptor Location	r ²	a(gm ² /yr)	b	Receptor Excluded
Canada	0.76	0.24	1.49	
Canada	0.84	0.16	1.48	11
U.S.	0.09	0.73	0.34	
U.S.	0.47	0.05	0.98	24, 25, 26
All PT	0.19	0.67	0.58	
All PT	0.51	0.24	1.04	11, 24, 25, 26
All PT Cdn Obs Reduced 30%	0.70	0.12	0.97	11, 24, 25, 26

Table 3

Model Emission Inventory for the Sudbury Region
(10³ tonnes SO₂/year)

Scenario	Details of Emissions	Total SO ₂ Emission
'Base Case'	INCO (1977)	1137
	Falconbridge	200
	Area and small point sources	20
		1357
Shut-down/ Strike Period	INCO (mean 78-79)	487
	Falconbridge (mean 78-79)	102
	Area and small pts	20
		609
INCO, Aug. 1980 Control Order	INCO Maximum Limit	
	Aug. 28, 1980	830
	(2500 short tons/day)	
	Falconbridge Limit	154
	(465 short tons/day)	
	Area and small pts	20
		1004
INCO, 1983 Control Order	INCO Maximum Limit	
	June 1, 1983	647
	(1950 short tons/day)	
	Falconbridge Limit	154
	(465 Short tons/day)	
	Area and small pts	20
		821

Note: When limits are original given in short tons the metric equivalents are round to nearest 10³ tonnes.

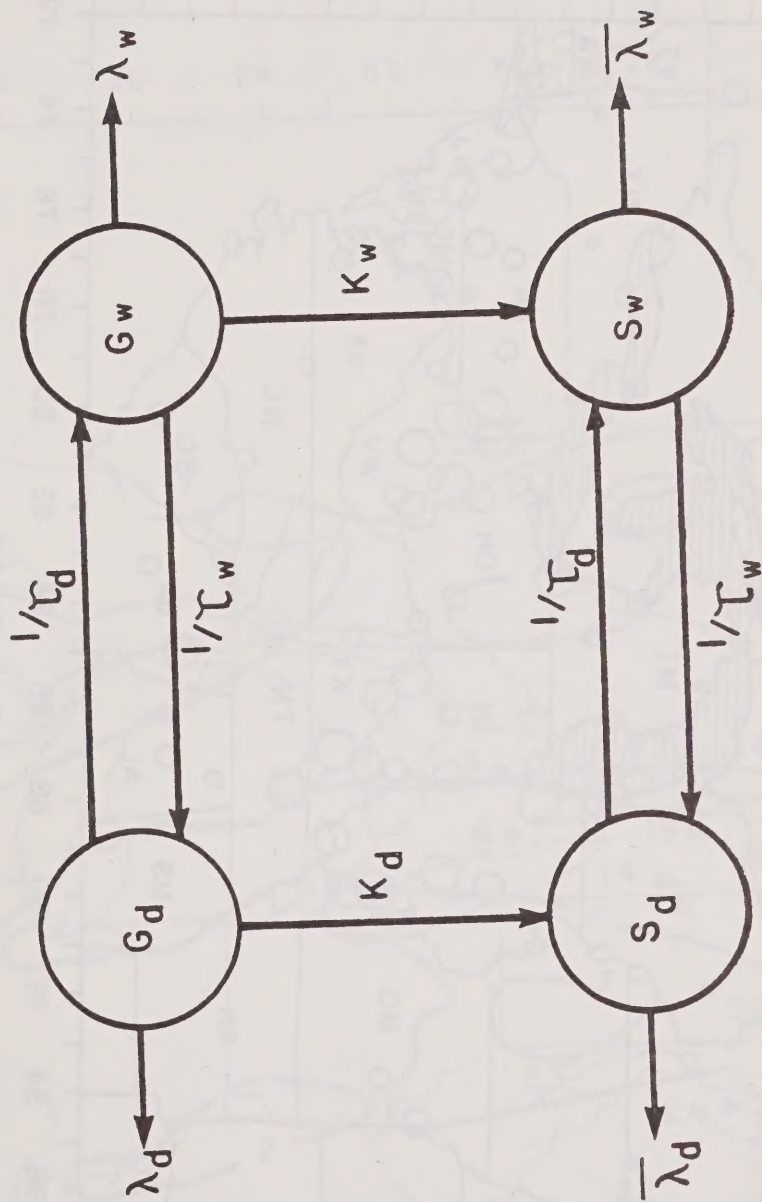


Figure 1. Schematic diagram of the scavenging model.

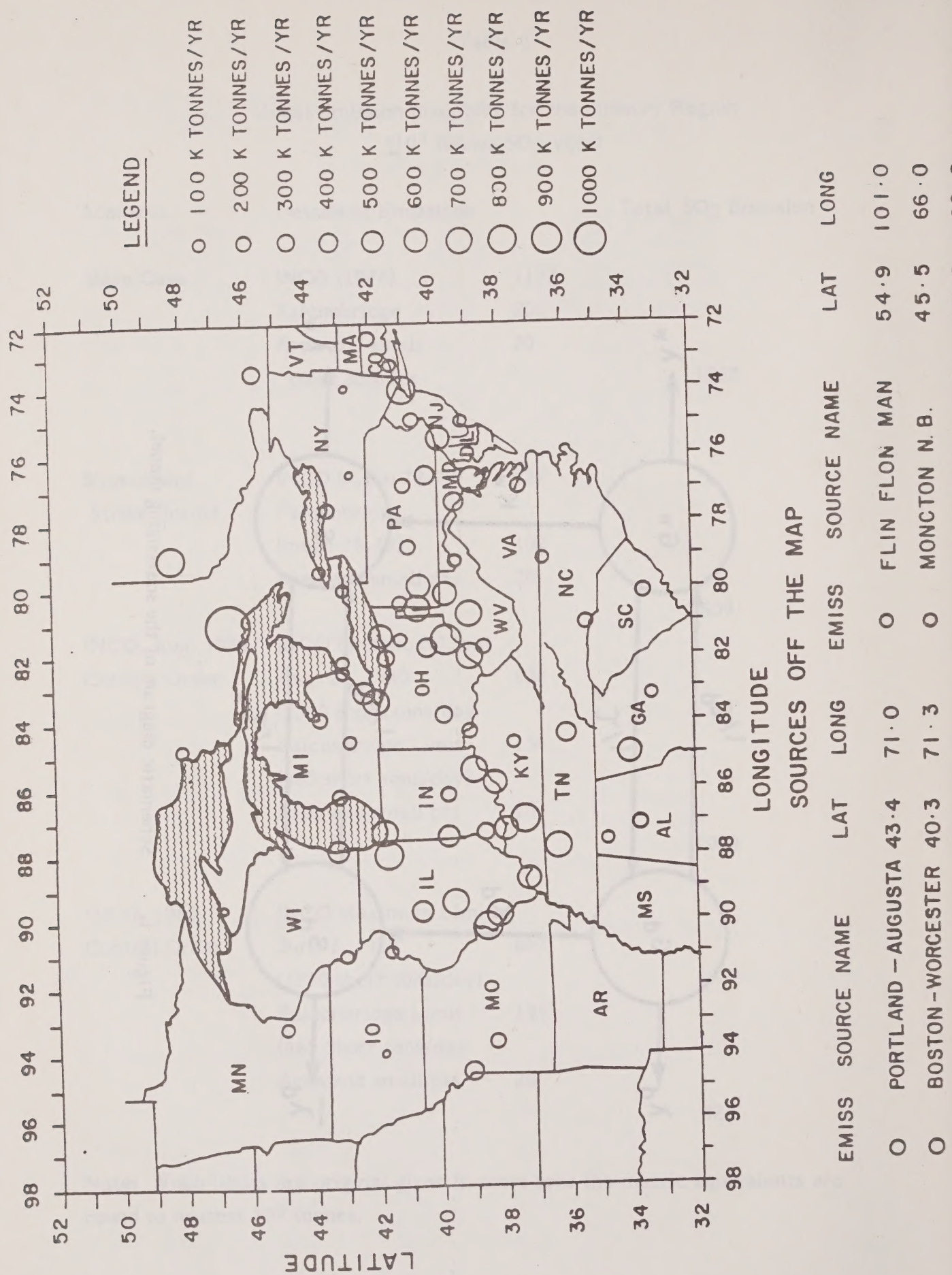


Figure 2. Distribution and relative magnitude of model SO₂ emission inventory.

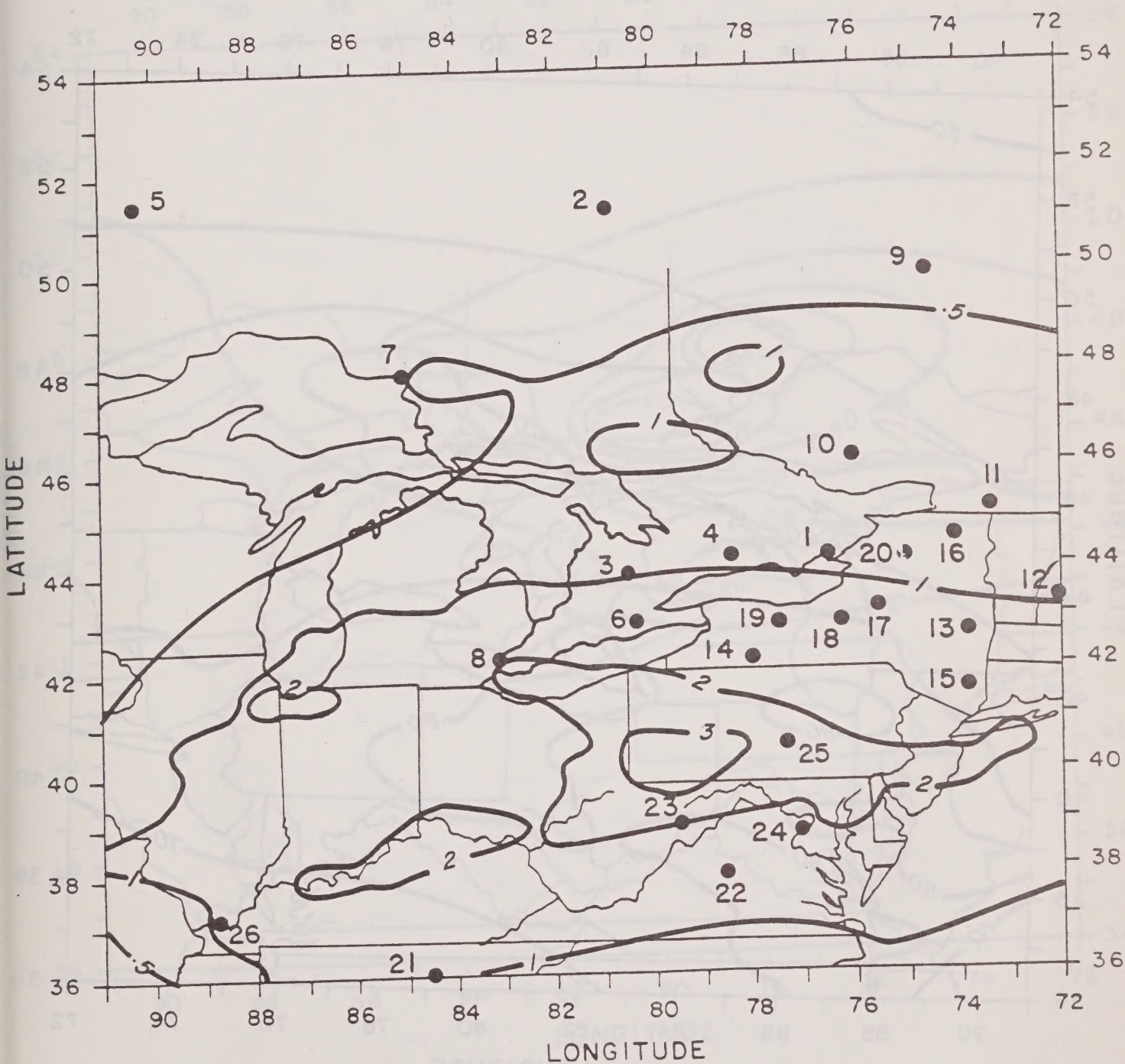


Figure 3. Model predictions of annual wet deposition of sulfur in $\text{gm/m}^2/\text{year}$. Stars in figure correspond to monitors in the CANSAP and U.S. networks. Numbers next to stars are station codes referred to in Table 2.

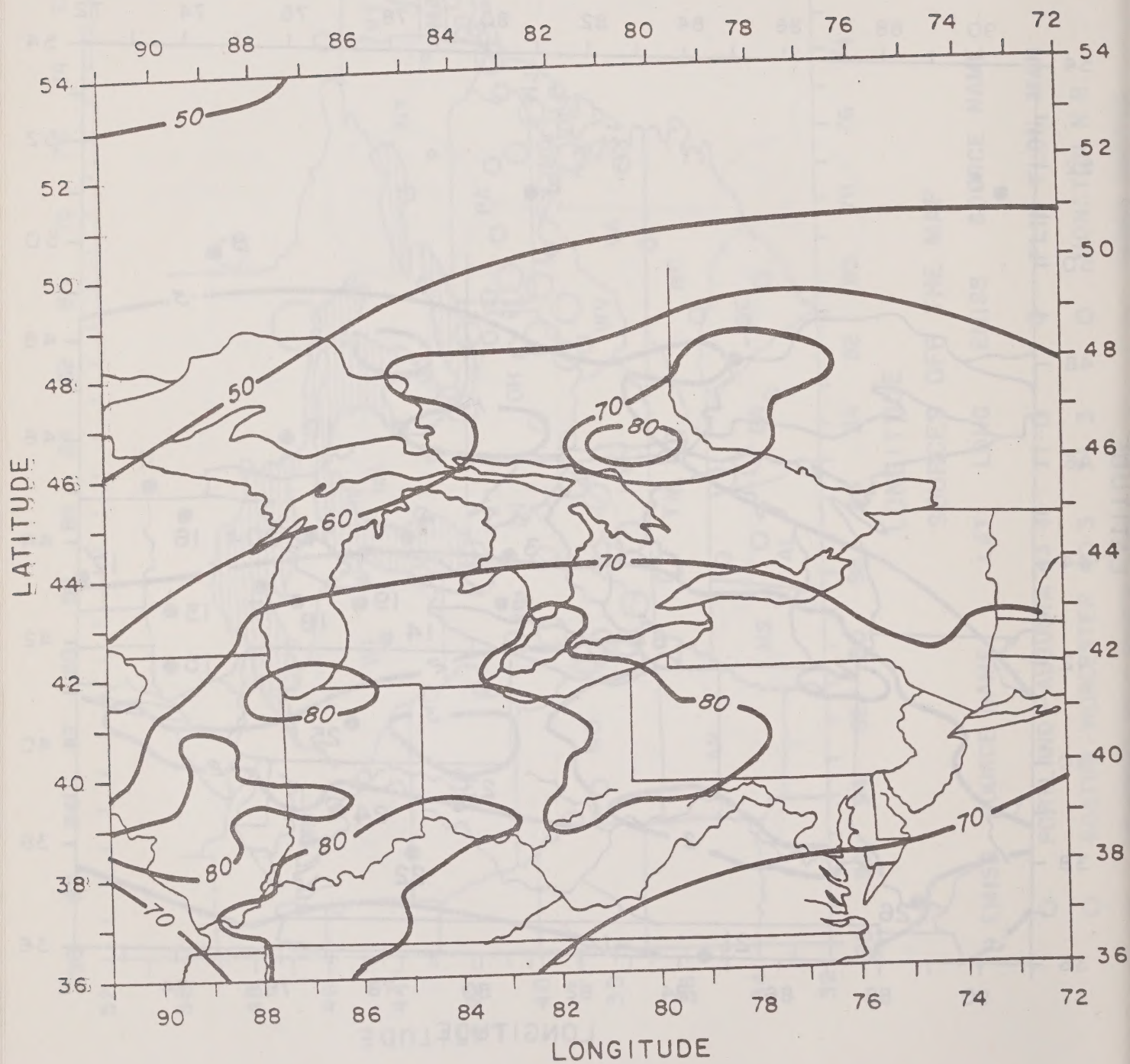


Figure 4. Relative contribution of SO₂ to the total wet deposition of sulfur.

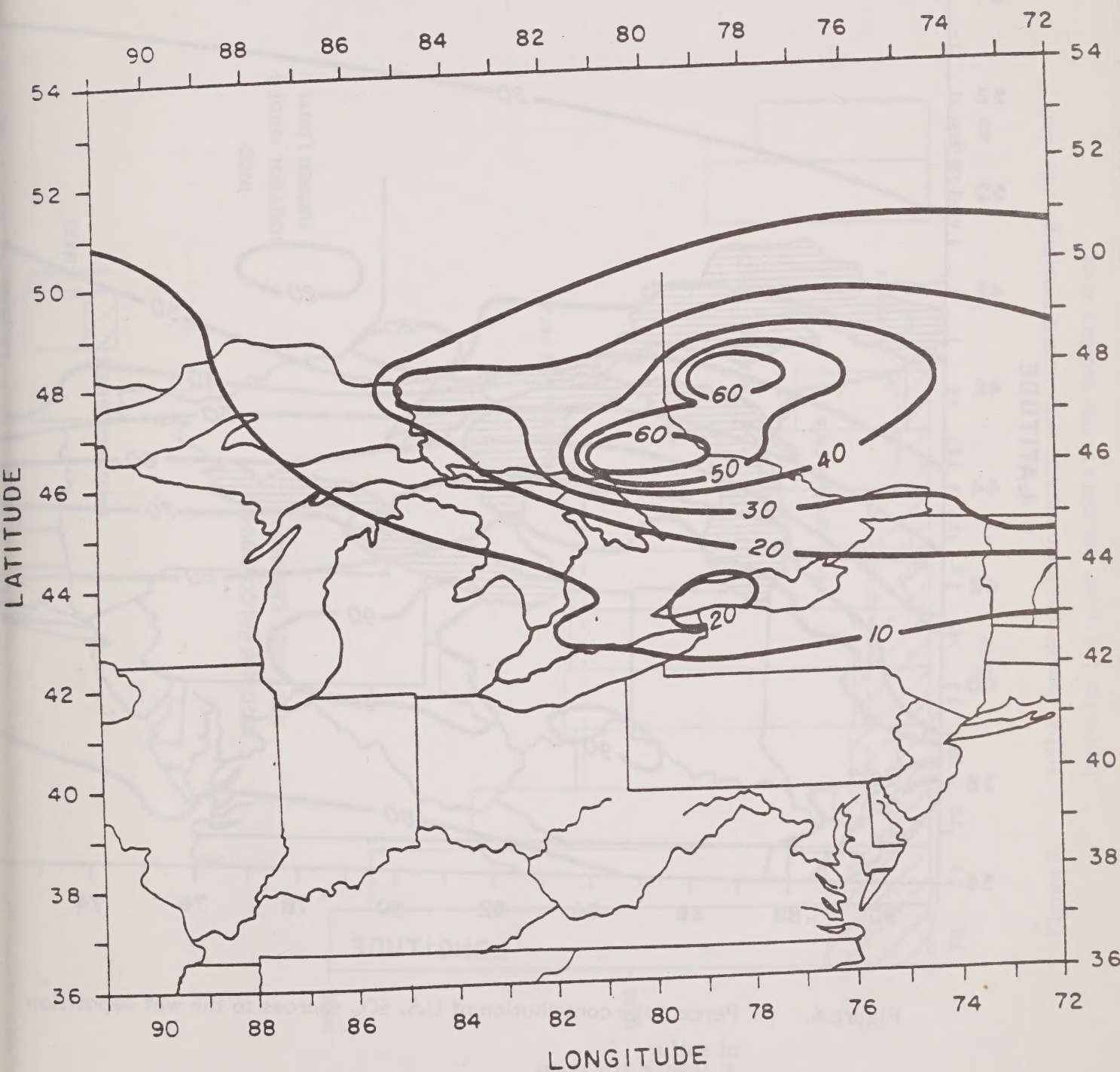


Figure 5. Percentage contribution of Canadian SO_x sources to the wet deposition of sulfur.

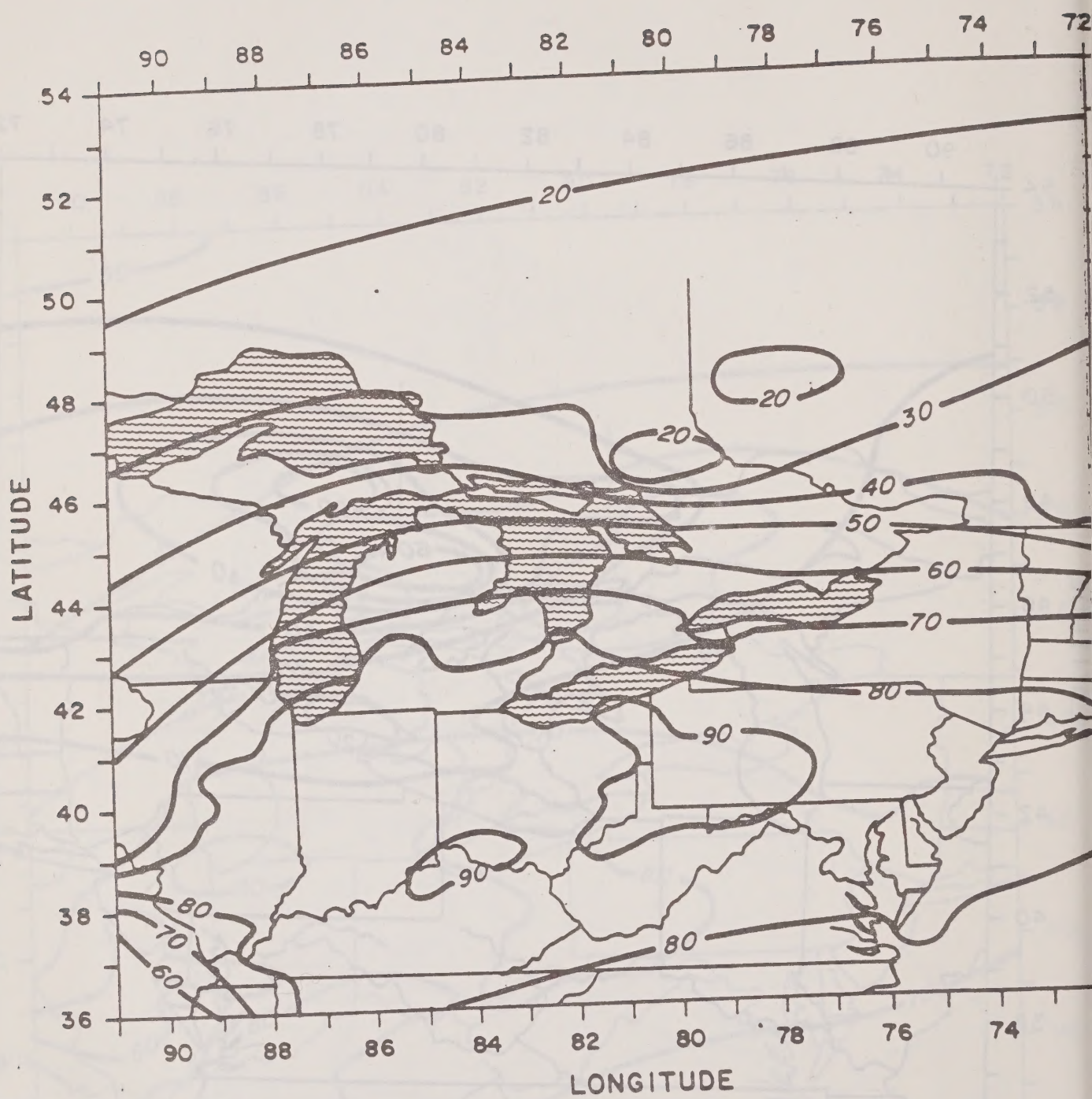


Figure 6. Percentage contribution of U.S. SO_x sources to the wet deposition of sulfur.

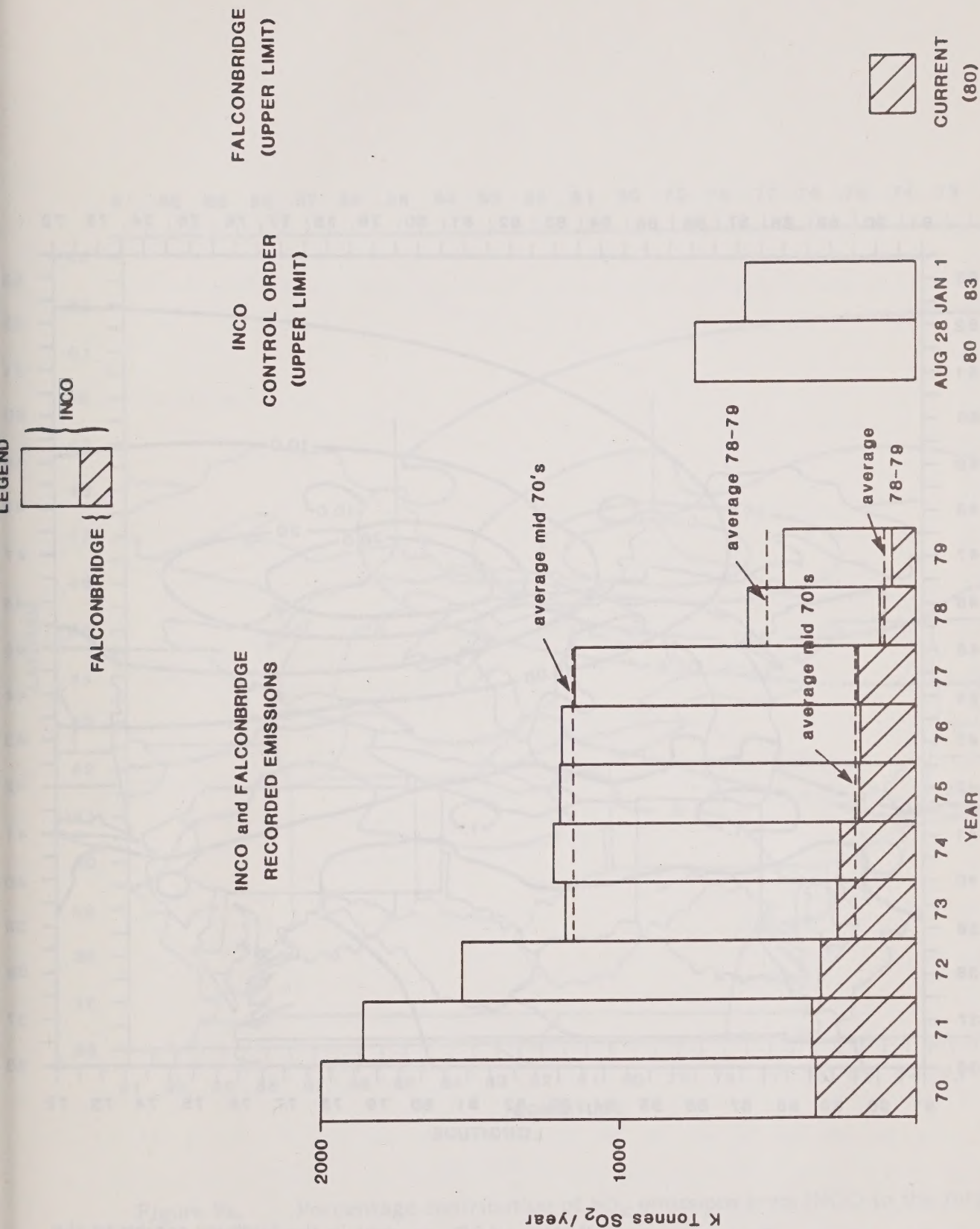


Figure 7. Sulfur dioxide emission records and current maximum emission limits for the major emitters in the Sudbry area.

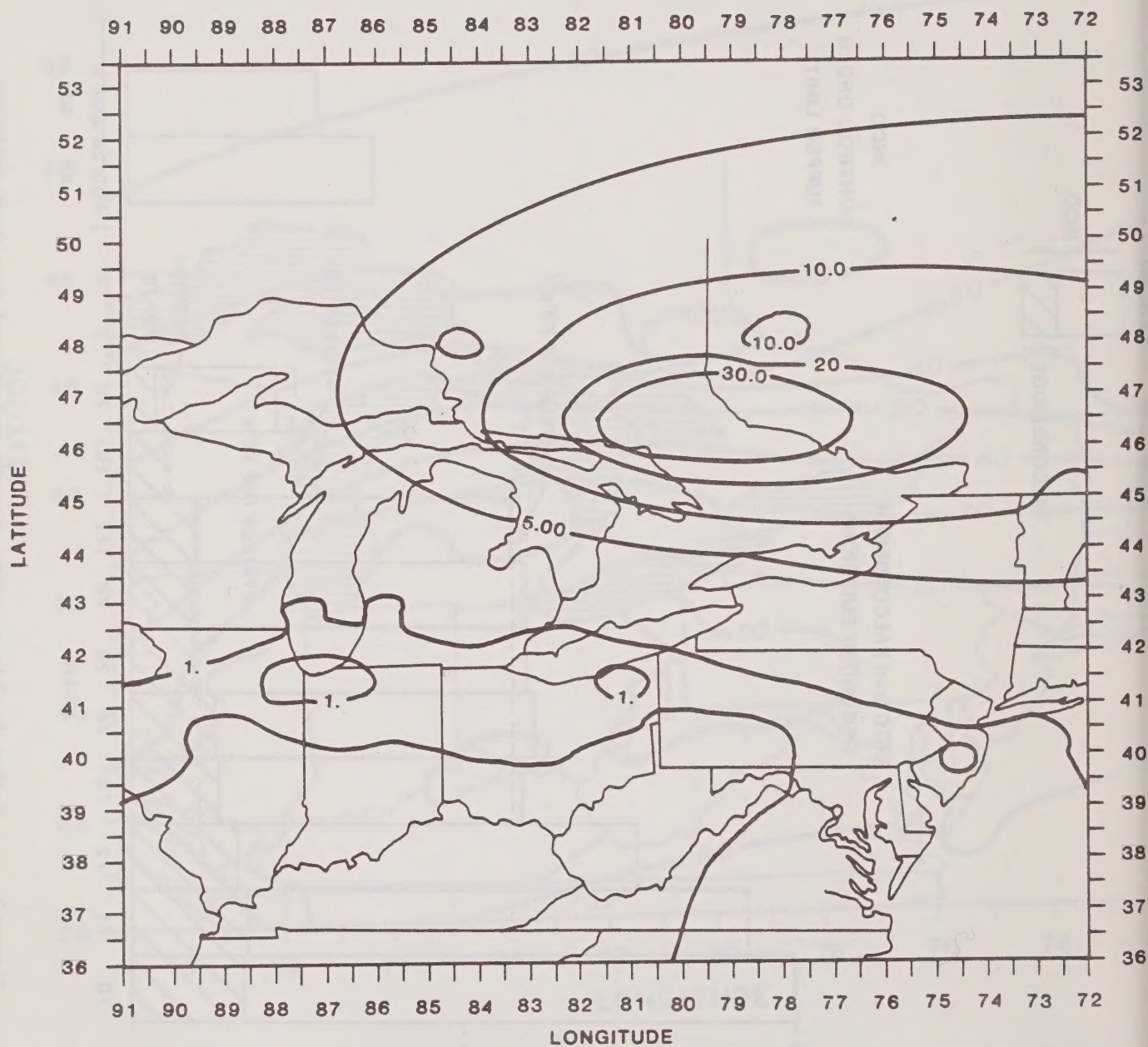


Figure 8. Percentage contribution of SO_x sources in the Sudbury region to the total wet deposition of sulfur.

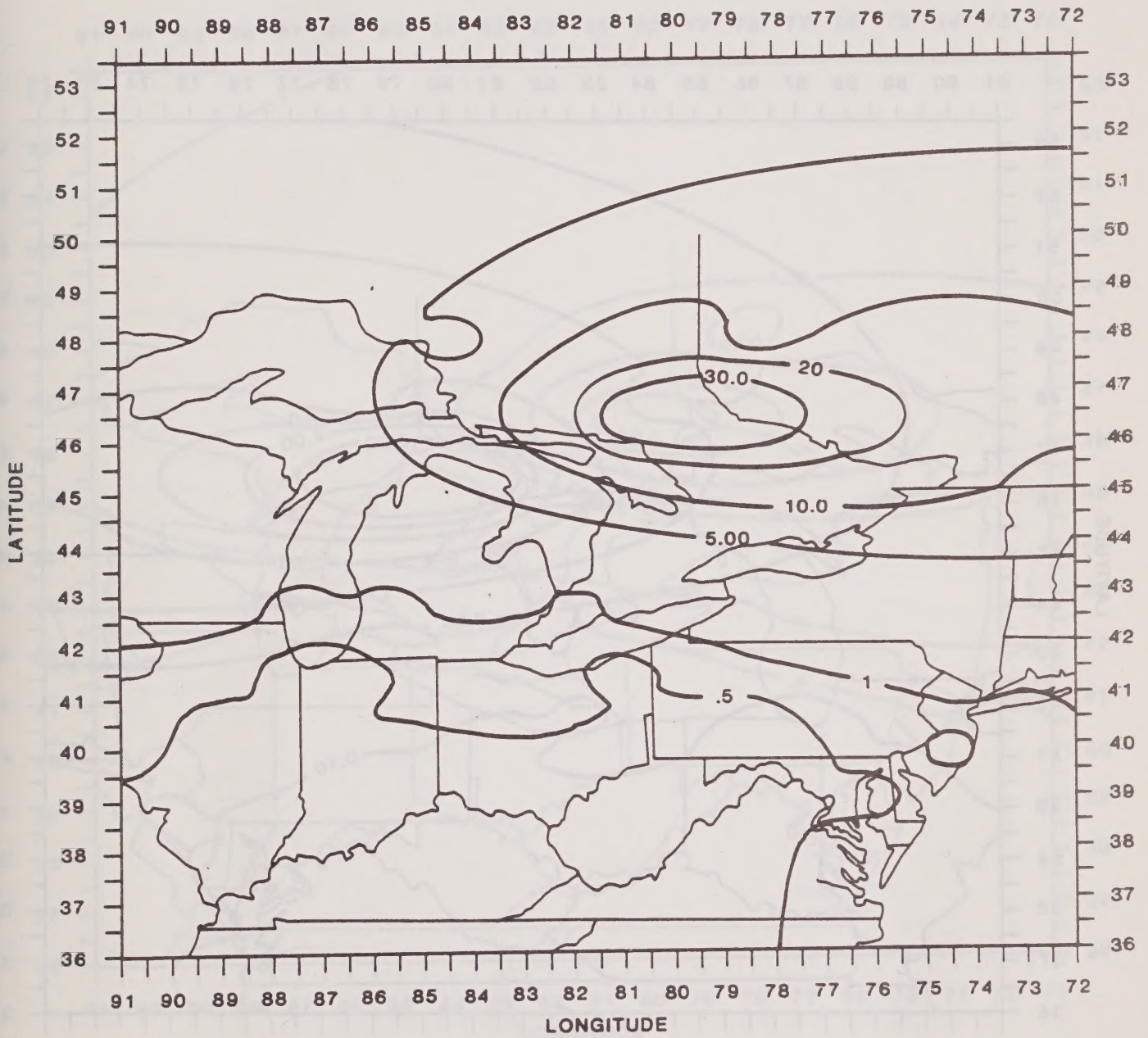


Figure 9a. Percentage contribution of SO_x emissions from INCO to the total wet deposition of sulfur.

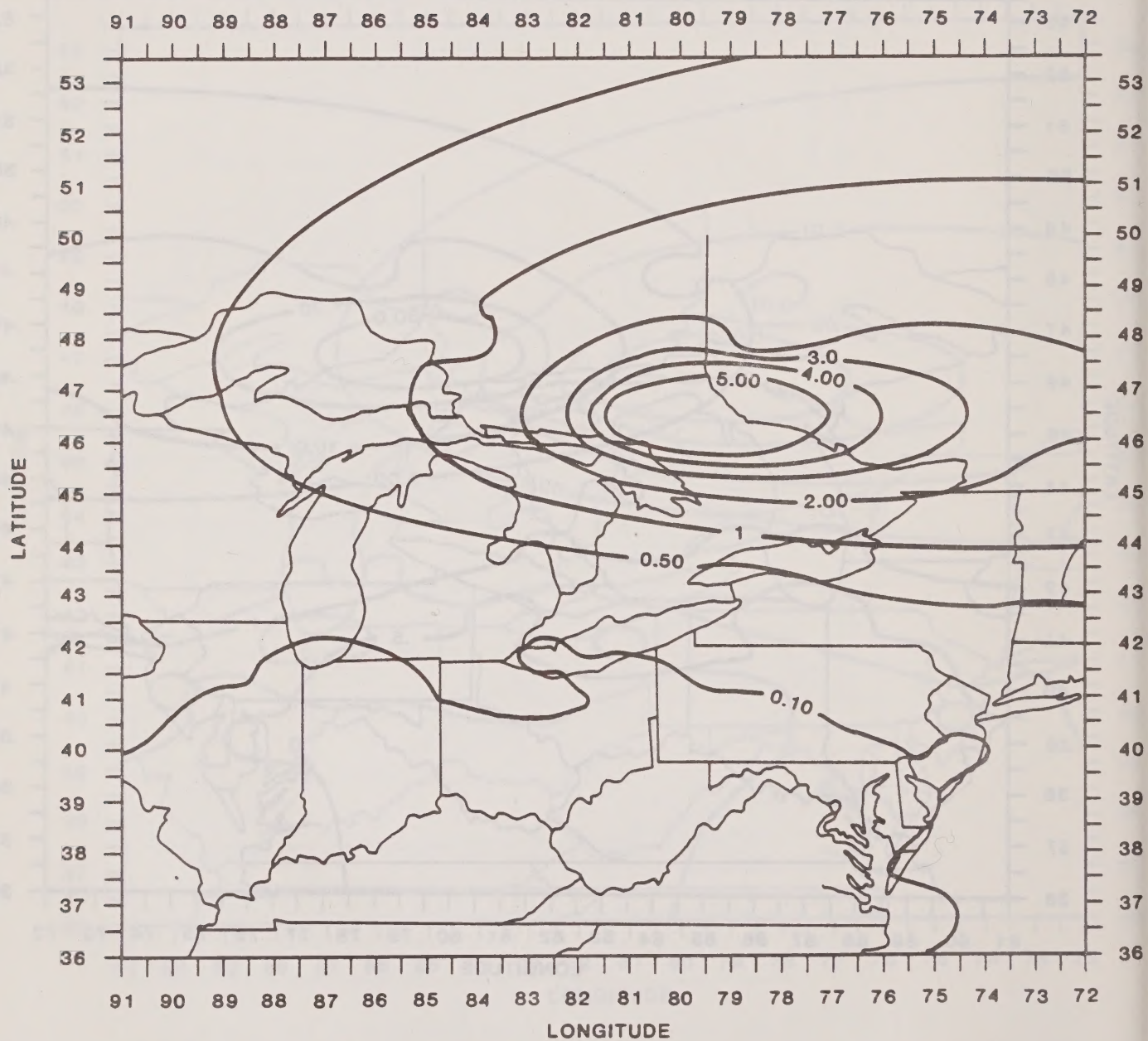


Figure 9b. Percentage contribution of SO_x emissions of SO_x emissions from Falconbridge to the total wet deposition of sulfur.

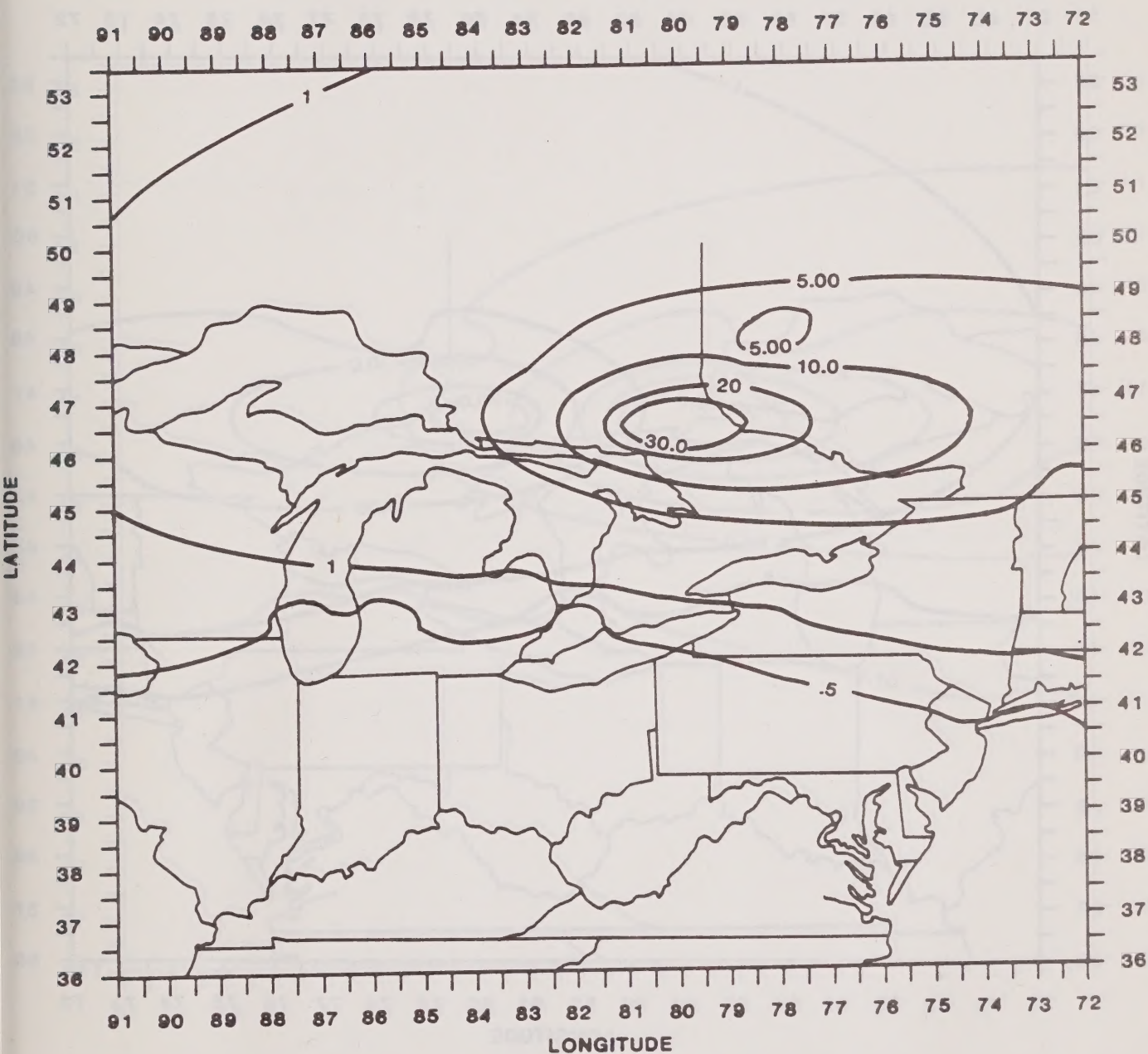


Figure 10. Percentage contribution of SO_x sources in the Sudbury region to the total wet deposition of sulfur during the strike/shut-down years 1978-79.

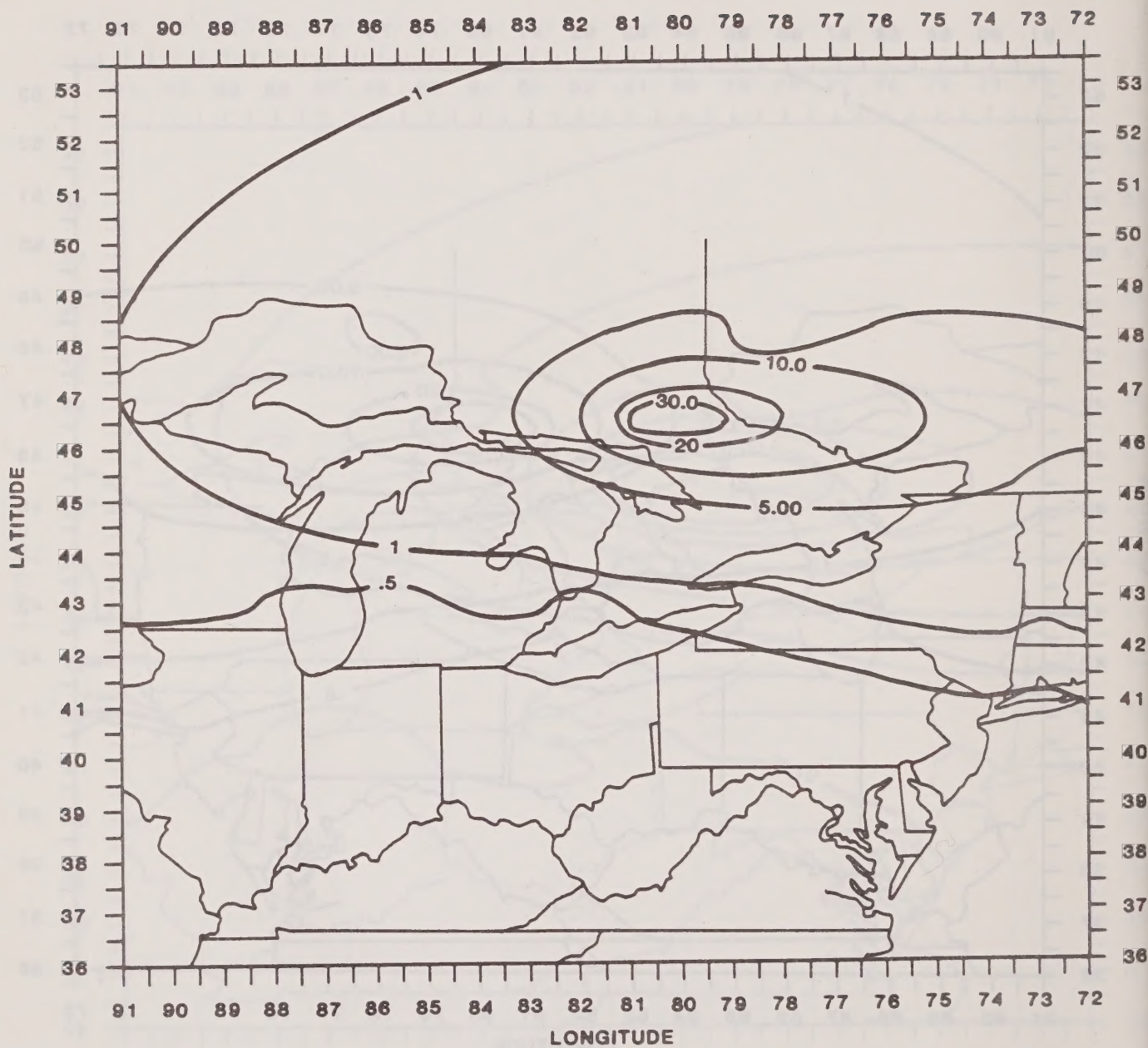


Figure 11a. Percentage contribution of SO_x emissions from INCO to the total wet deposition of sulfur during 1978-79.

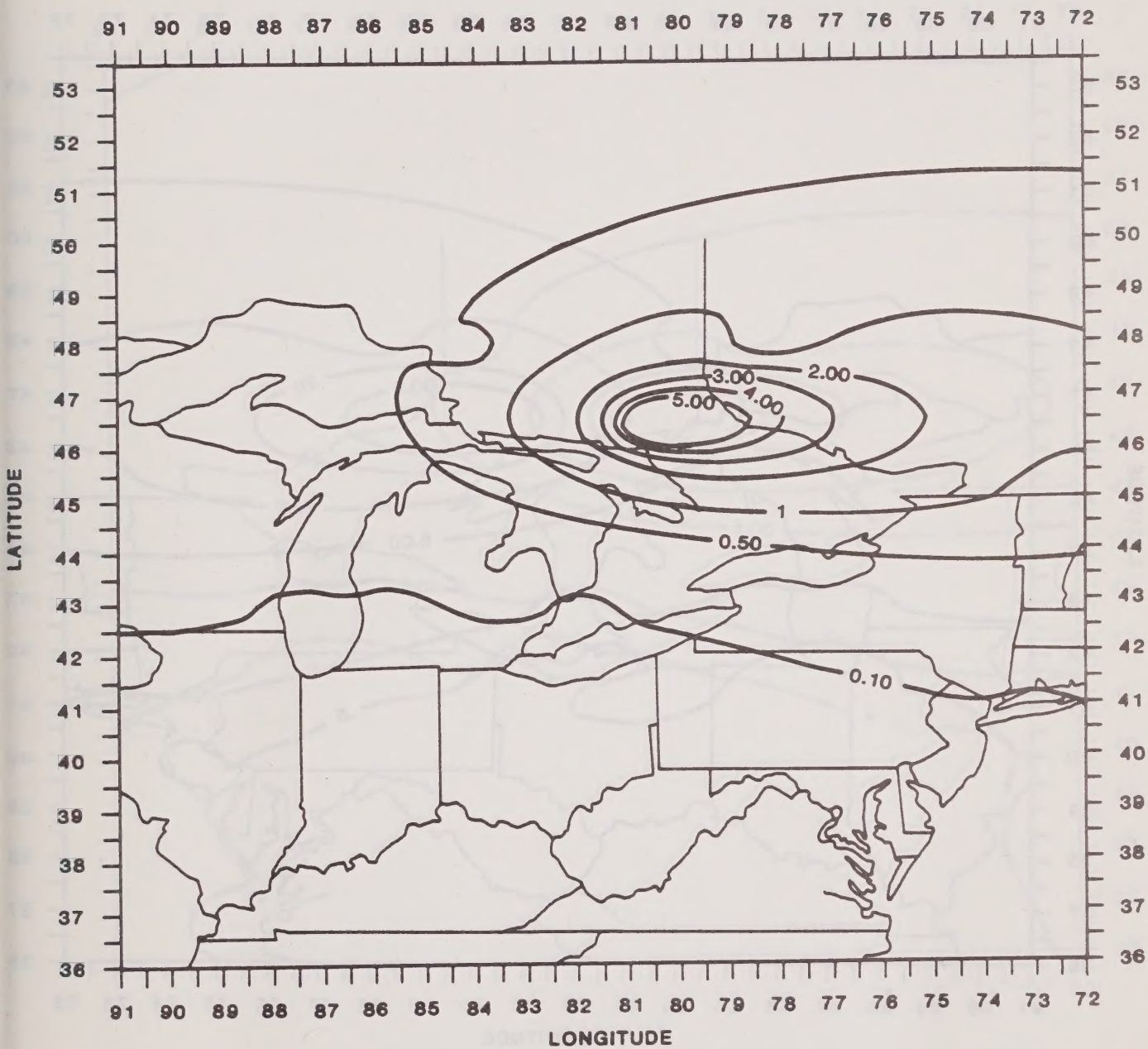


Figure 11b. Percentage contribution of SO_x emissions from Falconbridge to the total wet deposition of sulfur during 1978-79.

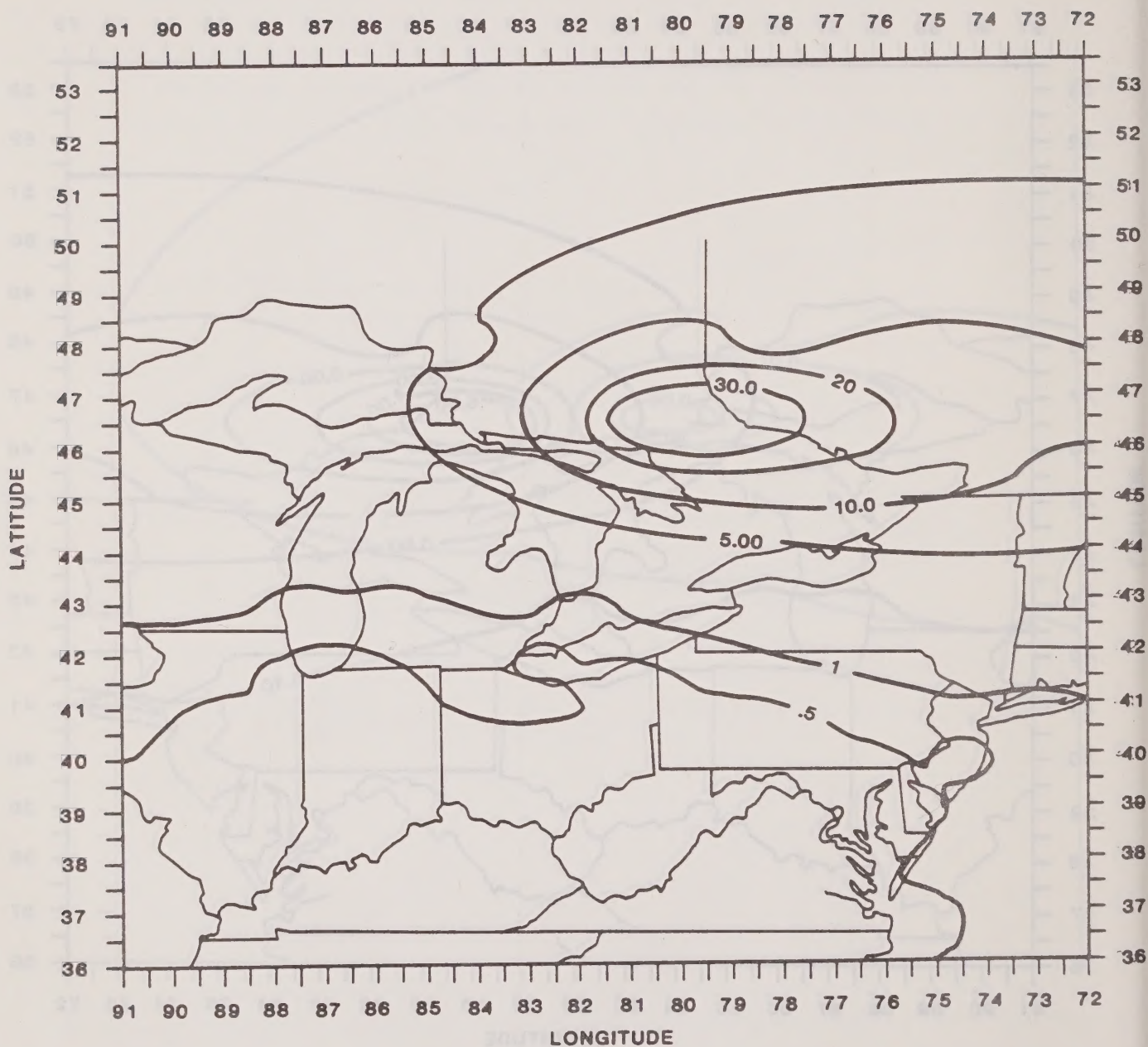


Figure 12. Estimated percentage contribution of SO_x sources in the Sudbury region to the wet deposition of sulfur assuming INCO's emissions are the maximum currently (Dec. 1980) allowable under the August 28, 1980 Control Order and Falconbridge's emissions are the maximum currently allowable.

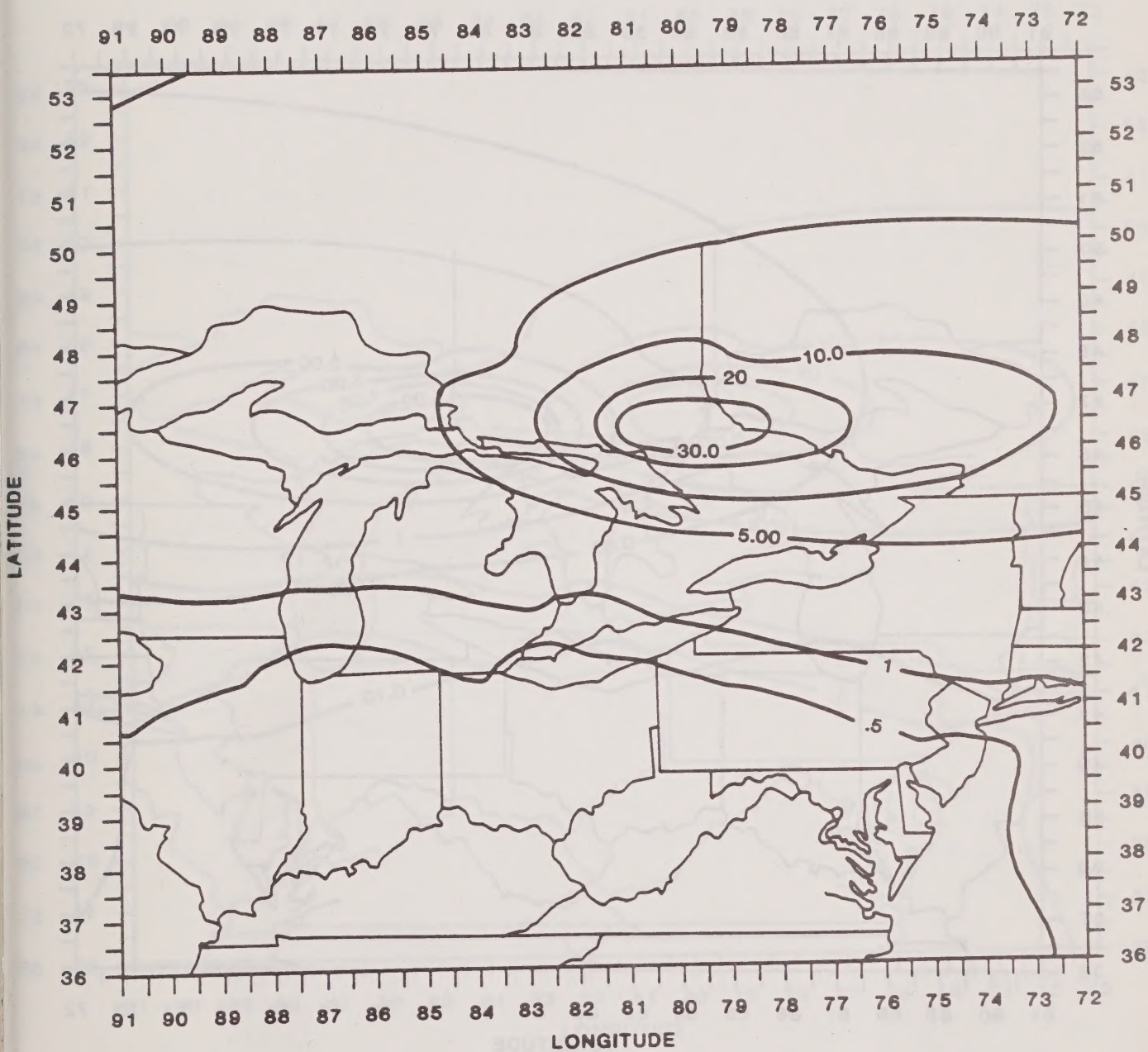


Figure 13a. Estimated percentage contribution of SO_x emissions from INCO to the wet deposition of sulfur assuming INCO's emissions are the maximum currently allowable under the August 28, 1980 Control Order.

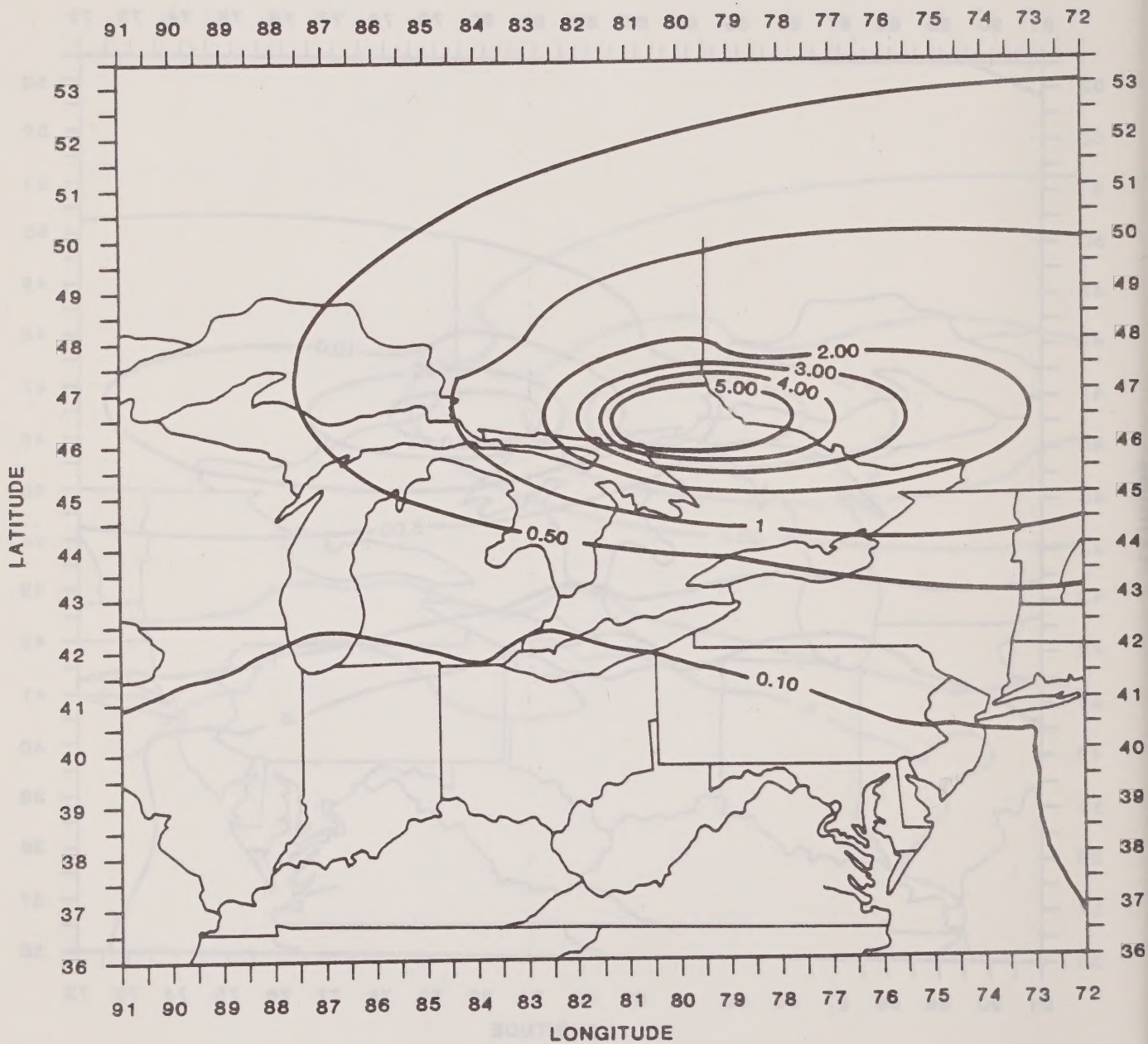


Figure 13b. Estimated percentage contribution of SO_x emissions from Falconbridge to the wet deposition of sulfur assuming Falconbridge's emissions are the maximum allowable under the current limits.

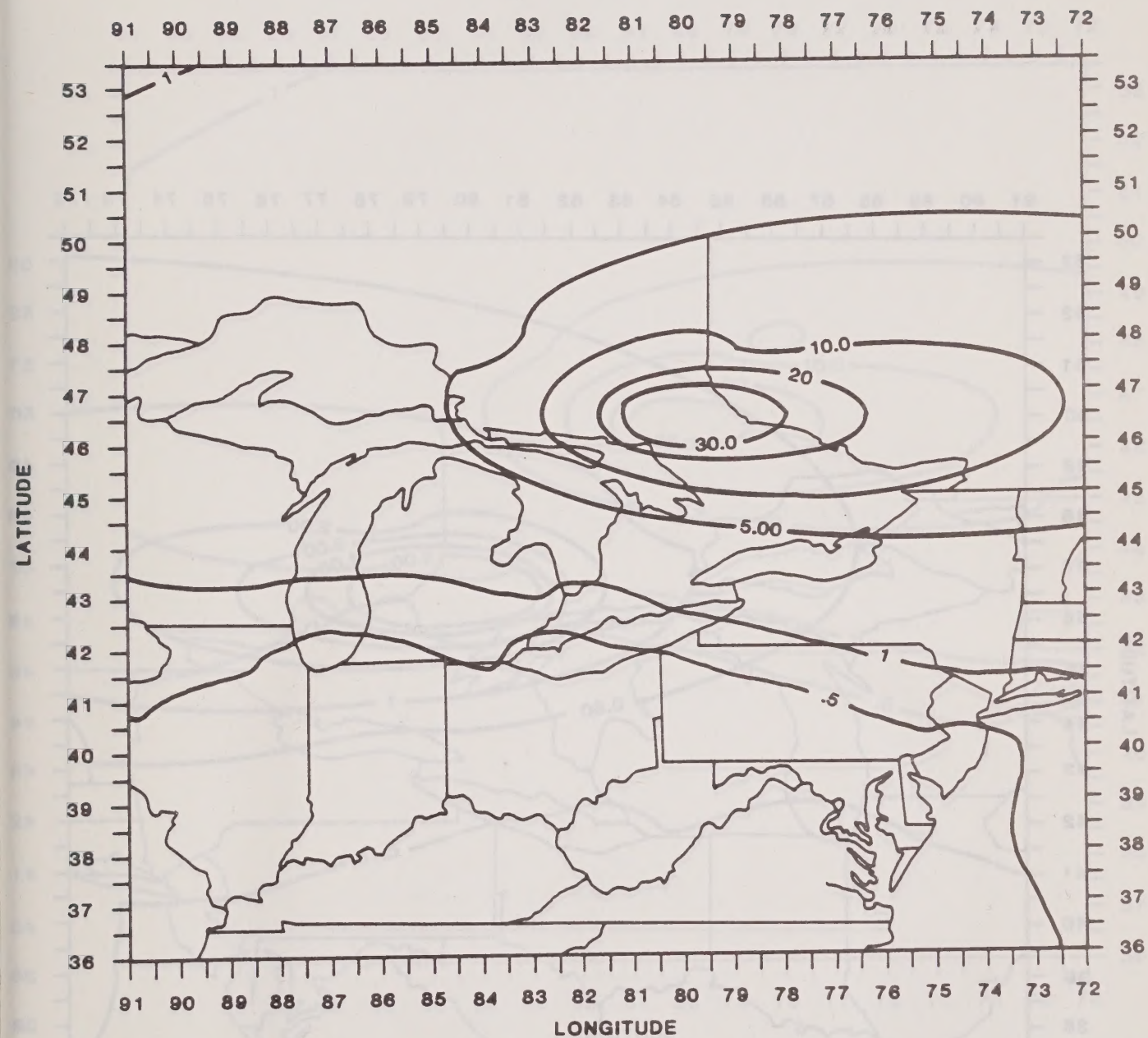


Figure 14.

Estimated percentage contribution of SO_x sources in the Sudbury region to the wet deposition of sulfur assuming Falconbridge's emissions are the maximum currently allowable and INCO's emissions are the maximum allowable after December 31, 1982, under the August 28, 1980 Control Order.

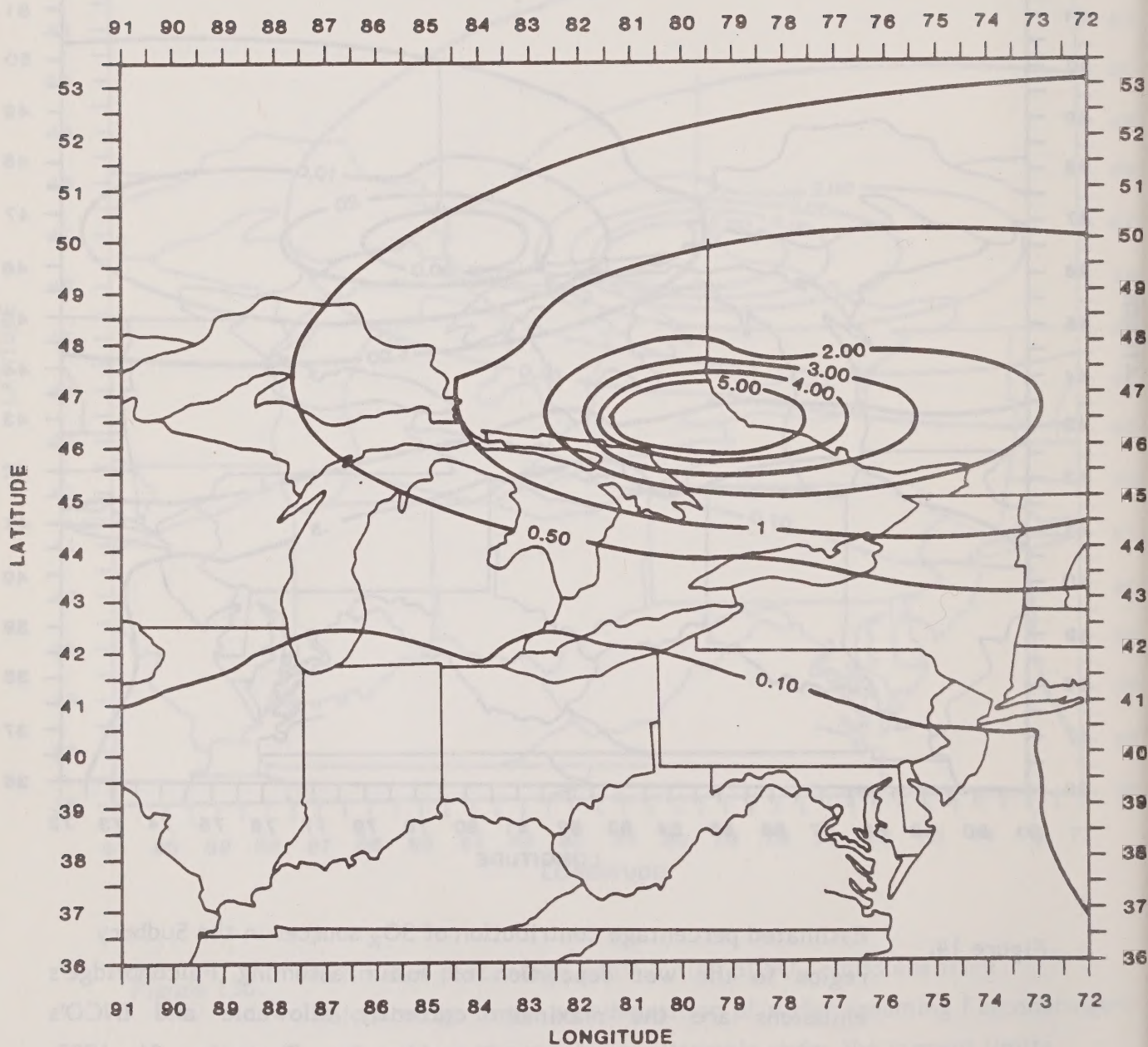


Figure 15a. Estimated percentage contribution of SO_x emissions from INCO to the wet deposition of sulfur assuming the same emission limits as in Figure 14 for Falconbridge and INCO.

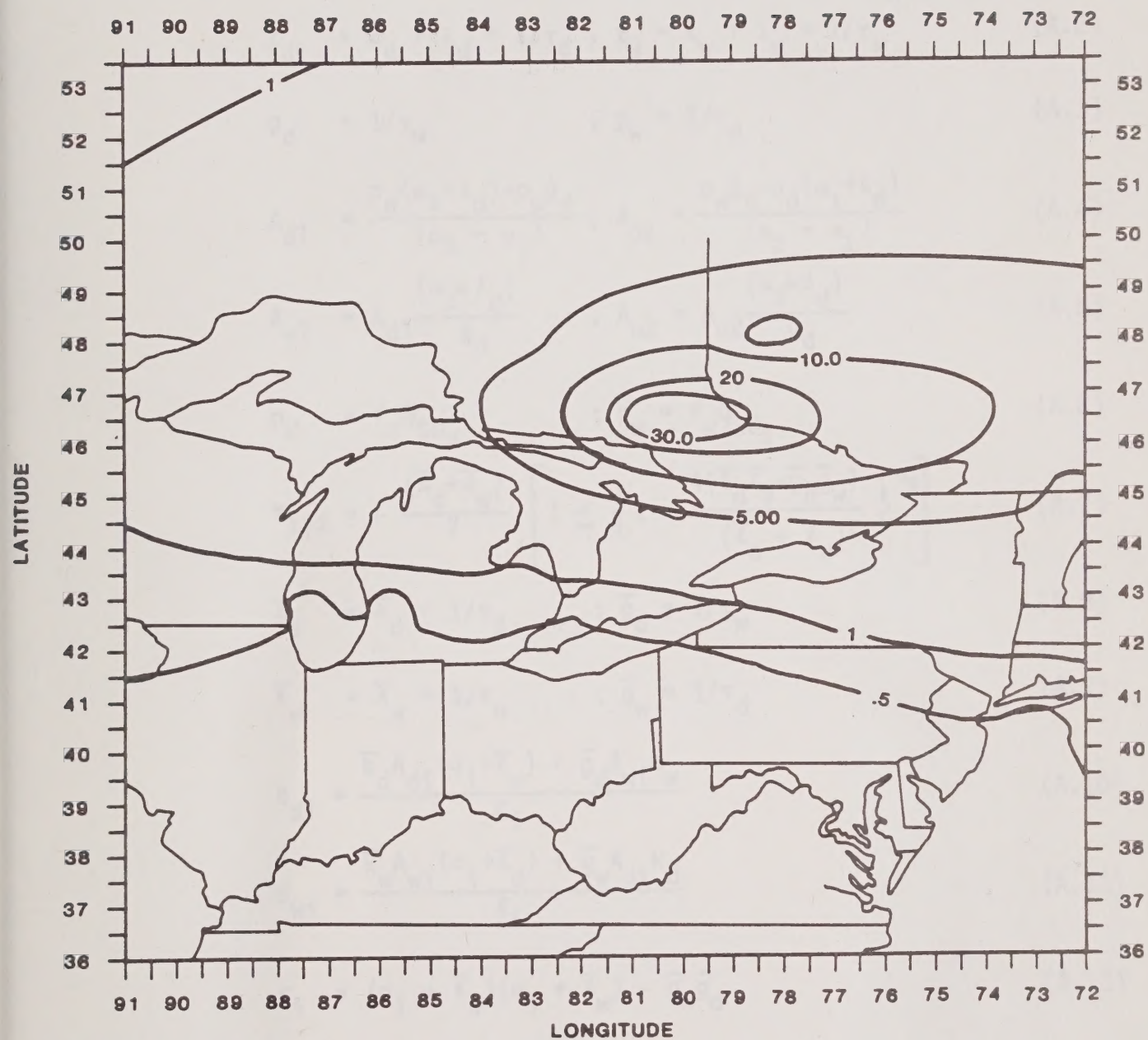


Figure 15b. Estimated percentage contribution of SO_x emissions from Falconbridge to the wet deposition of sulfur assuming the same emission limits as in Figure 14 for Falconbridge and INCO.

The constants in equations (4a) and (4b) are given by:

$$\alpha_{1,2} = - \frac{(\ell_d + \ell_w)}{2} \left[1 \pm \left\{ 1 - \frac{4(\ell_d \ell_w - g_d g_w)}{(\ell_d + \ell_w)^2} \right\}^{\frac{1}{2}} \right] \quad (A.1)$$

where

$$\ell_d = k_d + \lambda_d + 1/\tau_d ; \ell_w = k_w + \lambda_w + 1/\tau_w \quad (A.2)$$

$$g_d = 1/\tau_w ; g_w = 1/\tau_d \quad (A.3)$$

$$A_{d1} = \frac{p_d(\alpha_2 + \ell_d) - p_w g_d}{(\alpha_2 - \alpha_1)} ; A_{d2} = \frac{p_w g_d - p_d(\alpha_1 + \ell_d)}{(\alpha_2 - \alpha_1)} \quad (A.4)$$

$$A_{w1} = A_{d1} \frac{(\alpha_1 + \ell_d)}{g_d} ; A_{w2} = A_{d2} \frac{(\alpha_2 + \ell_d)}{g_d} \quad (A.5)$$

$$p_d = f_d Q_{SO_2} ; p_w = f_w Q_{SO_2} \quad (A.6)$$

$$\gamma_{1,2} = - \frac{(\bar{\ell}_d + \bar{\ell}_w)}{2} \left[1 \pm \left\{ 1 - \frac{4(\bar{\ell}_d \bar{\ell}_w - \bar{g}_d \bar{g}_w)}{(\bar{\ell}_d + \bar{\ell}_w)^2} \right\}^{\frac{1}{2}} \right] \quad (A.7)$$

$$\bar{\ell}_d = \bar{\lambda}_d + 1/\tau_d ; \bar{g}_d = 1/\tau_w \quad (A.8)$$

$$\bar{\ell}_w = \bar{\lambda}_w + 1/\tau_w ; \bar{g}_w = 1/\tau_d \quad (A.9)$$

$$\beta_{di} = \frac{\bar{k}_d A_{di}(\alpha_i + \bar{\ell}_w) + \bar{g}_d A_{wi} k_w}{\xi_i} \quad (A.10)$$

$$\beta_{wi} = \frac{\bar{k}_w A_{wi}(\alpha_i + \bar{\ell}_d) + \bar{g}_w A_{di} k_d}{\xi_i} \quad (A.11)$$

$$\xi_i = (\alpha_i + \bar{\ell}_d)(\alpha_i + \bar{\ell}_w) - \bar{g}_w \bar{g}_d \quad (A.12)$$

and

$$B_{d1} = \frac{v_d(\gamma_2 + \bar{\ell}_d) - v_w \bar{g}_d}{(\gamma_2 - \gamma_1)} ; B_{d2} = \frac{v_d \bar{g}_d - v_w(\gamma_1 + \bar{\ell}_d)}{(\gamma_2 - \gamma_1)} \quad (A.13)$$

$$B_{w1} = \frac{B_{d1}(\gamma_1 + \bar{\ell}_d)}{\bar{g}_d} ; B_{w2} = \frac{B_{d2}(\gamma_2 + \bar{\ell}_d)}{\bar{g}_d} \quad (A.14)$$

where

$$v_d = - \sum_{i=1}^2 \beta_{di} + f_d Q_{SO_4} ; v_w = - \sum_{i=1}^2 \beta_{wi} + f_w Q_{SO_4} \quad (A.15)$$

$$\bar{k}_d = \frac{3}{2} k_d ; \bar{k}_w = \frac{3}{2} k_w \quad (A.16)$$

Doc. No.	Corporate Author:
CA 2 ONEV	Ont. M.O.E.
58	Series:
81	Rept. # ARB-36-81-SES
SES	Title: Stat'l Model to Estimate Long-term Concentrations...
Date:	

RESOURCE CENTRE
INST. FOR ENVIRON'L. STUDIES
UNIVERSITY OF TORONTO



